

# **ENVIRONMENTAL ASSESSMENT**

## **OCEAN SEQUESTRATION OF CO<sub>2</sub> FIELD EXPERIMENT**

**PACIFIC INTERNATIONAL CENTER FOR HIGH TECHNOLOGY RESEARCH**

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## **Cover Sheet**

**Proposed Action:** An international consortium that includes the U.S. Department of Energy (DOE) would participate in an experiment to evaluate the dispersion and diffusion of liquid carbon dioxide droplets in ocean waters. The experiment would be conducted in 2002. If the action is approved, the consortium would conduct a series of tests involving the intermittent release of liquid carbon dioxide at a depth between 2,600 and 3,280 feet (800 – 1,000 meters). The carbon dioxide would be supplied through flexible tubing from a surface vessel to a nozzle attached to a retrievable platform resting on the ocean floor. All testing would be completed within a two-week period. Monitoring of the released carbon dioxide droplets would be accomplished using a combination of remotely operated vehicles controlled from surface vessels, a submersible, and bottom arrays of measurement equipment.

A number of alternative ocean sites were considered for conduct of the proposed experiment. Candidate ocean sites within the U.S. territorial waters included several locations offshore from the Hawaiian Islands and in the Gulf of Mexico, off the coast of Louisiana. The decision to seek an Ocean Dumping Permit for the existing N\_wiliwili Ocean Disposal Site was reached following review of these alternatives and discussions with U.S. Environmental Protection Agency staff in Region IX, Region VI, and headquarters.

Discharge of liquid carbon dioxide from a surface vessel through tubing to a nozzle attached to a bottom-located platform is preferred. Generally, ocean locations possessing the following characteristics would be appropriate for the experiment: seafloor within the 800 – 1,000 meter depth range; weather and surface wave conditions suitable for completing the experiment; proximity to land-based support facilities; and absence of natural resources that would be adversely affected.

**Abstract:** This Environmental Assessment (EA) concludes that the most notable change from the experiment would be a temporary increase in acidity resulting from the dissolution of liquid carbon dioxide droplets into the seawater. The dissolving carbon dioxide droplets would achieve steady vertical and lateral conditions within one hour (models estimate about 30 minutes) following the start of the release. Modeling indicates that acidity levels that could affect marine organisms for approximately 30 minutes after each 2-hour release is stopped (i.e., less than three hours total). After that time the action of ocean currents would return acidity to background levels. Comparative studies of the effects on marine organisms at levels of acidity comparable to and greatly exceeding the levels anticipated for the experiment suggest that exposure of this magnitude would not produce adverse effects.

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**LIST OF ACRONYMS AND ABBREVIATIONS**

ACM	Acoustic Current Meter
ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
C	Centigrade
CDUP	Conservation District Use Permit
CEQ	Council on Environmental Quality
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
cm	centimeters
cm/s	centimeters per second
CO <sub>2</sub>	carbon dioxide
COE	U.S. Army Corps of Engineers
CTD	conductivity, temperature, depth probe
CTI	Climate Technology Initiative
CWB	Clean Water Branch (DOH)
CZM	Coastal Zone Management
DAR	Division of Aquatic Resources (DLNR)
dB	decibels
DBEDT	Department of Business, Economic Development & Tourism (State of Hawai‘i)
DIC	Dissolved Inorganic Carbon
DLNR	Department of Land and Natural Resources (State of Hawai‘i)
DOE	U.S. Department of Energy
DOH	Department of Health (State of Hawai‘i)
EA	Environmental Assessment
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
<i>et al.</i>	and others
F	Fahrenheit
FAD	Fish Aggregation Device
FCCC	Framework Convention on Climate Change (United Nations)
FETC	Federal Energy Technology Center (DOE) (now known as the National Energy Technology Laboratory) (NETL)
FY	fiscal year
GHG	greenhouse gas
GtC	billion metric tons (gigatons) of atmospheric carbon
HAR	Hawai‘i Administrative Rules
HDPE	high-density polyethylene



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HIBT	Hawaiian International Billfish Tournament
HRS	Hawai‘i Revised Statutes
HURL	Hawai‘i Undersea Research Laboratory
Hz	Hertz (cycles per second)
IEA	International Energy Agency
<i>in situ</i>	In place
IOS	Institute of Ocean Sciences (Canada)
IPCC	Intergovernmental Panel on Climate Change
kg/s	kilograms (2.2 pounds) per second
kHz	kilohertz
km	kilometer(s)
kW	kilowatts
l	liter(s)
m	meters
m <sup>2</sup>	square meters
m <sup>3</sup>	cubic meters
MARPOL	International Convention for the Prevention of Pollution from Ships
mg/l	milligram(s) per liter
MIT	Massachusetts Institute of Technology
mmol	milli-moles
_Pa	micro-Pascals
MMPA	Marine Mammal Protection Act
NASA	National Atmospheric and Space Administration
NEDO	New Energy and Industrial Technology Development Organization
NELH	Natural Energy Laboratory of Hawai‘i
NELHA	Natural Energy Laboratory of Hawai‘i Authority
NEPA	National Environmental Policy Act
NERSC	Nansen Environmental and Remote Sensing Center (Norway)
NETL	National Energy Technology Laboratory (DOE) (formerly known as Federal Energy Technology Center)
NIVA	Norwegian Institute for Water Research
NMFS	National Marine Fisheries Service
NODC	National Oceanographic Data Center
NPDES	National Pollutant Discharge Elimination System
NPSG	North Pacific Subtropical Gyre
NRC	Norwegian Research Council
OGCM	Ocean Global Climate Model
OHA	Office of Hawaiian Affairs (State of Hawai‘i)
OS	U.S. Department of Energy, Office of Science
OSHA	Occupational Safety and Health Administration

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p <sub>a</sub>	Partial Pressure of CO <sub>2</sub> in the atmosphere
p <sub>m</sub>	Partial Pressure of CO <sub>2</sub> in the mixed layer of the ocean
pH	Standard measure of acidity; the negative logarithm (base 10) of the hydronium (H <sub>3</sub> O <sup>+</sup> ) molar activity. The lower the pH (on a scale of 1 to 14), the higher the acidity. Pure water has a pH of 7 (i.e., is neither acidic nor basic). Normal surface ocean water has a pH of about 8 to 8.5, and deep (800 m) ocean water has a pH of about 7.6. By way of comparison, lemon juice has a pH of 2, and most carbonated soft drinks have a pH of about 4.
PICHTR	Pacific International Center for High Technology Research
ppm	parts per million
ppmv	parts per million by volume
R&D	Research and Development
RITE	Research Institute of Innovative Technology for the Earth (Japan)
ROV	Remotely operated vehicle
RTV	Remotely operated television
SHPO	State Historic Preservation Office (DLNR)
SMA	Special Management Area
U.S.	United States
USC	United States Code

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

#### 1.1.1 OVERVIEW OF THE PROPOSED ACTION

A consortium of international organizations is proposing to participate in an experiment to evaluate the dispersion and diffusion of liquid carbon dioxide droplets in ocean waters. The project is referred to as the “Ocean Sequestration of CO<sub>2</sub> *Field Experiment*” (referred to subsequently as the *Field Experiment*). If approved, it would be conducted over approximately two weeks some time in the first half of 2002.

The proposed *Field Experiment* involves the intermittent release of liquid carbon dioxide at a depth of approximately 2,950 feet (900 meters). The carbon dioxide would be supplied at flow rates of between 1.6 and 9.5 gallons per minute (0.1 to 0.6 kg/sec) through flexible tubing from a surface vessel to a nozzle attached to a retrievable platform resting on the ocean floor. The released carbon dioxide droplets and changes in seawater chemistry would be monitored using a combination of remotely operated vehicles controlled from surface vessels, a submersible, and bottom arrays of measurement equipment. Dispersion of the CO<sub>2</sub> into liquid droplets would be achieved using a specially designed discharge nozzle attached to the platform. The experiment would provide information for future use in considering options that might be necessary for effectively managing the build-up of carbon dioxide (a greenhouse gas) in the atmosphere. The N\_wiliwili Ocean Disposal Site possesses the weather and wave conditions and proximity to land-based logistical support needed for the experiment.

The *Field Experiment* would provide information on (1) physical and chemical changes induced in seawater by releasing liquid CO<sub>2</sub> and (2) relationships between release parameters (e.g., flow rate, injection velocity) and the physical dynamics of CO<sub>2</sub> droplets. In addition, sampling of biota and naturally occurring bacteria populations in the vicinity of the discharge nozzle would be conducted to provide insight into potential biological responses resulting from the short-term exposure to CO<sub>2</sub>.

#### 1.1.2 PREVIOUS ENVIRONMENTAL DOCUMENTATION AND PERMIT APPLICATIONS

The U.S. Department of Energy has addressed the potential effects of the proposed experiment in a recently completed Environmental Assessment (DOE/EA-1336). At the time the Environmental Assessment (EA) was prepared, the preferred site for the *Field Experiment* was within the Ocean Research Corridor of the Natural Energy Laboratory of Hawai‘i Authority (NELHA) at Ke\_hole Point, Island of Hawai‘i. Consequently, that site was described in greatest detail in the EA. However, the EA also described the characteristics and potential environmental consequences of conducting the experiment within ocean waters outside the Ocean Research Corridor. DOE published the Final EA in March 2001.

The NELHA site that was discussed in greatest detail in the EA was located less than three miles from the shoreline. Hence, it was subject to the NPDES regulations that the State of Hawai‘i Department of Health has adopted pursuant to the Clean Water Act and implementing regulations. Conducting the proposed *Field Experiment* at that location did not require EPA approval.

Subsequent to completion of the EA for the *Field Experiment*, and in response to concerns expressed by the public both inside and outside the NEPA process, PICHTR identified three alternate sites within the Hawaiian Islands region. One of these locations was the N\_wiliwili Ocean Disposal Site. The N\_wiliwili Dredged Material Disposal Site is located more than three miles from the shoreline. Both the State of Hawai‘i Department of Health and the U.S. Environmental Protection Agency have determined that releases more than three miles from shore that do not originate from pipelines or other facilities extending from the shoreline are not subject to the NPDES regulations.

## INTRODUCTION

While it has been determined that no NPDES permit would be needed to conduct the experiment at the N\_wiliwili Dredged Material Disposal Site, the EPA has ruled that releases such as those that would result from the Ocean Sequestration of CO<sub>2</sub> *Field Experiment* constitute “dumping” and require a “Research Permit” as provided for in 40 CFR Part 220.3(e), which reads:

*(e) Research permits. Research permits may be issued for the dumping of any materials, other than materials specified in §227.5 or for any of the materials listed in §227.6 except as trace contaminants, unless subject to the exclusion of §227.6(g), into the ocean as part of a research project when it is determined that the scientific merit of the proposed project outweighs the potential environmental or other damage that may result from the dumping. Research permits shall specify expiration date no later than 18 months from the date of issue.*

CO<sub>2</sub> is not one of the prohibited materials listed in §227.5. Neither is it one of the materials listed in §227.6. Thus, EPA has determined that it has the statutory authority to issue a Research Permit for the release.

### 1.1.3 PURPOSE OF THIS DOCUMENT

This administrative EA was prepared to assist the U.S. Environmental Protection Agency in fulfilling its responsibilities under the National Environmental Policy Act (NEPA) of 1969 [42 United States Code 4321 et seq.], the Council on Environmental Quality’s Regulations [Title 40, Code of Federal Regulations (CFR), Parts 1500-1508], and the Department of Energy’s NEPA Implementing Procedures [Title 10, CFR, Part 1021]. It identifies and assesses potential environmental impacts that could result from conducting the *Field Experiment* within the existing N\_wiliwili Ocean Disposal Site.

## 1.2 PURPOSE AND NEED FOR THE *FIELD EXPERIMENT*

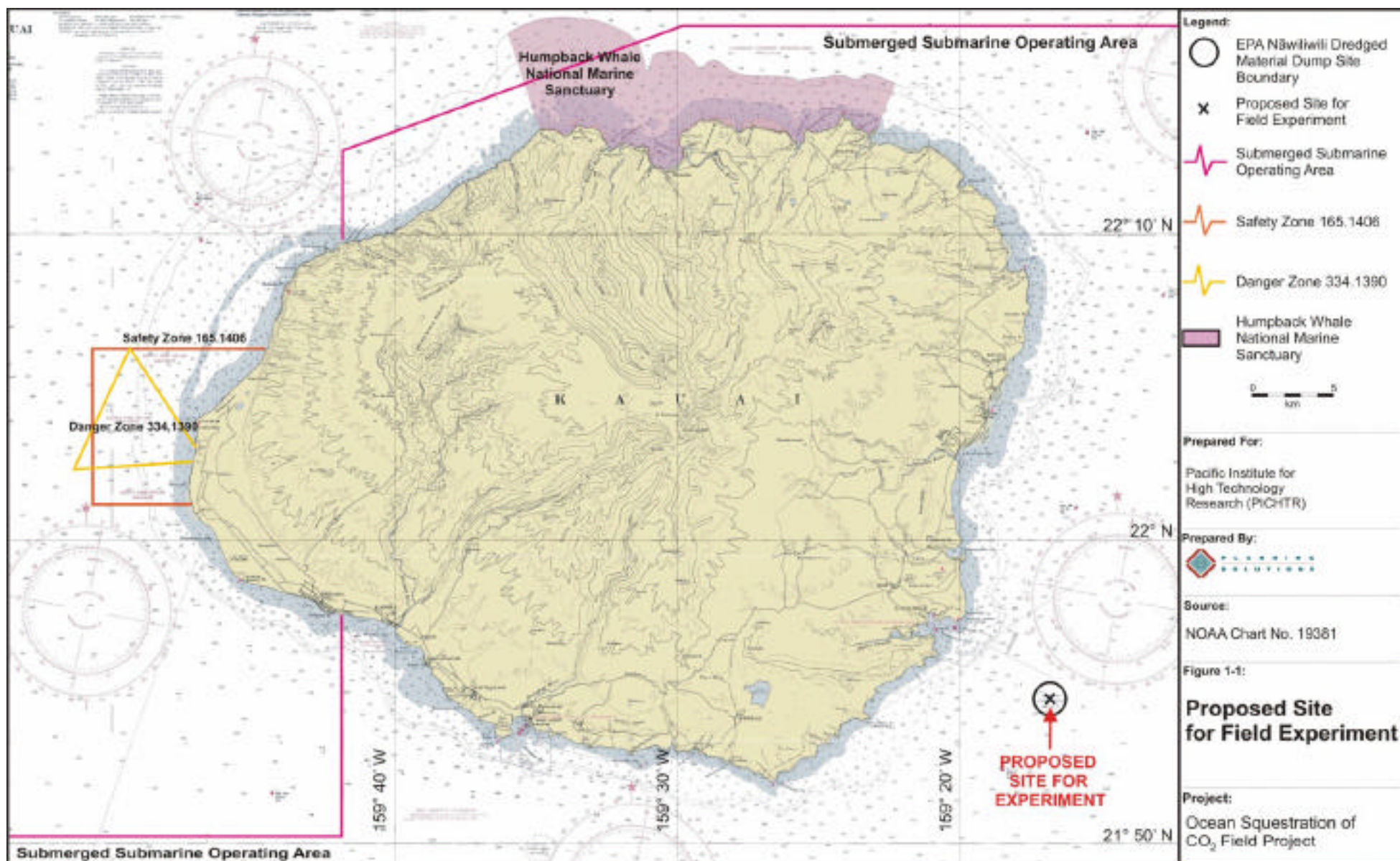
The *Field Experiment* would provide data to confirm scientific predictions and to test and refine theoretical models scientists use to predict the behavior of liquid CO<sub>2</sub> released into the ocean at moderate depths (2,300-4,900 feet; about 700-1,500 meters).

## 1.3 THE FIELD EXPERIMENT SCHEDULE

The *Field Experiment* would be conducted during a two week period in the first half of 2002. It would consist of up to ten 2-hour-long releases .

## 1.4 SUMMARY OF EFFECTS

Table 1-1 summarizes the potential environmental effects of conducting the *Field Experiment* at the N\_wiliwili Ocean Disposal Site.



**Table 1-1. Anticipated Impacts**

<b>RESOURCE AFFECTED</b>	<b><i>FIELD EXPERIMENT</i> At the N_wiliwili Disposal Site</b>	<b>NO ACTION</b>
<b>Marine Water Quality</b>	Cloud of liquid CO <sub>2</sub> droplets up to 1,000 feet from discharge nozzle; temporary depression of pH	No or similar effects
<b>Seafloor</b>	Local abrasion of surface due to platform and pipe emplacement and movement.	No or similar effects
<b>Benthic Marine Life</b>	Potential for stress and mortality on benthic life immediately beneath discharge platform & pipeline and in areas subject to pH below 6.5	No or similar effects
<b>Deep-Water Pelagic Marine Life</b>	Very small loss of plankton and minor effects on mobile organism communities	No or similar effects
<b>Midwater Marine Life</b>	Very minor stress on local plankton populations	No or similar effects
<b>Surface-Water Marine Life</b>	No adverse effects	No or similar effects
<b>Historical and Cultural Resources</b>	No effects on archaeological or historic sites	No or similar effects
<b>Air Quality and Climate</b>	Emissions from engine exhaust. Experiment would help improve models used to evaluate climate change.	No or similar effects
<b>Noise</b>	No adverse effects	No or similar effects
<b>Marine Transportation</b>	Slightly increased vessel traffic for short periods during two-week experiment; some limits on vessel movement.	No or similar effects
<b>Land Use</b>	No effects	No effects
<b>Aesthetic Resources</b>	No effects	No effects
<b>Socioeconomic Resources</b>	Inputs of goods and services to Hawai'i communities; expenditures for goods where test equipment would be manufactured.	No or similar effects
<b>Public Facilities and Services</b>	No effects	No effects
<b>Public Safety &amp; Health</b>	No effects	No effects

## 2.0 PURPOSE AND NEED FOR AGENCY ACTION

### 2.1 BACKGROUND OF OCEAN SEQUESTRATION OF CO<sub>2</sub>

In the past 100 years, the amount of anthropogenic carbon dioxide (CO<sub>2</sub>) emitted into the atmosphere has greatly increased, primarily due to expanding use of fossil fuels. Scientists estimate that atmospheric CO<sub>2</sub> has risen from pre-industrial levels of 280 parts per million (ppm) to over 365 ppm (Keeling and Whorf 1998). Barring a major change in the way energy is produced and used, predictions of global energy use in the 21<sup>st</sup> century suggest a continued increase in carbon emissions and rising concentrations of CO<sub>2</sub> in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) estimated that future global emissions of CO<sub>2</sub> will increase from 7.4 billion metric tons of atmospheric carbon (GtC) annually in 1997 to approximately 26 GtC per year by 2100 (IPCC 1996).

Although historical effects of increased CO<sub>2</sub> levels on global climate remain a topic of debate, there is scientific consensus that doubling atmospheric CO<sub>2</sub> concentrations from present levels could have a variety of serious environmental consequences in the 21<sup>st</sup> century. There is growing evidence, for example, that higher concentrations of CO<sub>2</sub> and other “greenhouse” gases could be contributing to an observed increase in average global temperatures. A global average temperature increase of even a few degrees could lead to an accelerated rise in sea level, changes in weather patterns, and other atmospheric changes that would impact human health, water resources, land use, and other resources (EPA 2000).

While the long-term solution to this problem must include actions associated with use of fossil fuels (e.g., application of more efficient technologies, reductions in fossil fuel use), these actions could not, on their own, be implemented on a schedule that would quickly stabilize CO<sub>2</sub> levels. The sheer magnitude of the present reliance on fossil fuels and the growing energy demands throughout the world make it inevitable that the United States and other nation-states will continue to rely on fossil fuels for energy well beyond the 21<sup>st</sup> century. Accordingly, some forms of carbon sequestration — carbon capture, separation, and storage or reuse — could be needed to assist in mitigating global climate change.

Carbon sequestration complements two other approaches to carbon management that are being developed by the U.S. Department of Energy (DOE). The first approach increases the efficiency of primary energy conversion and end-use. DOE sponsors a variety of research and development (R&D) programs to investigate more efficient supply-side and demand-side technologies. These technologies include more efficient fossil fuel-fired power plants, buildings, appliances, and transportation vehicles. DOE also fosters research into methods of producing and delivering electricity and fuels more efficiently. More efficient energy conversion and end-use would result in lower CO<sub>2</sub> emissions per unit of energy service.

The second approach is substituting lower-carbon or carbon-free energy sources for current energy sources. Examples include using lower-carbon fossil fuels (e.g., replacing coal or oil with natural gas) and increasing renewable energy use (such as solar or wind). DOE has major R&D programs to develop more efficient fossil energy utilization and renewable energy technologies.

Carbon sequestration, the focus of the *Field Experiment* discussed in this Environmental Assessment (EA), represents a third approach to carbon management. Most effective over the mid-term, carbon sequestration would complement long-term efforts to improve efficiency and transition toward low-carbon fuels. Increased recognition of the urgency in dealing with the CO<sub>2</sub> buildup has focused more interest on the potential of this approach. In response, DOE has established R&D objectives intended to develop a better understanding of the economics and environmental implications of a variety of carbon sequestration technologies. Successful development and implementation of such technologies would allow the world to continue to benefit from the use of fossil fuels without the adverse side effects that result when CO<sub>2</sub> is emitted into the atmosphere. Federal participation in research on



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PURPOSE AND NEED FOR AGENCY ACTION

carbon sequestration technologies is important at this early stage in their development because technical uncertainties and lack of profit incentive discourage commitment of private resources.

The United Nations' Framework Convention on Climate Change (FCCC), adopted in 1992, called for industrialized nations to reduce their greenhouse gas (GHG) emissions to 1990 levels by the year 2000. This ambitious goal was viewed as an initial step for developed countries under FCCC, but the overarching objective was to stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Some 167 countries, including the United States, have ratified FCCC. The International Energy Agency (IEA) established the Climate Technology Initiative (CTI) in 1995, as part of an effort by industrialized nations to fulfill the demands of FCCC. The Kyoto Protocol, negotiated by the nation-states of the world in December 1997, may be viewed in the same way.

CTI (<http://www.climatech.net/home.shtml>) seeks to increase the use of existing and new climate-friendly technologies through international cooperation in research, development, deployment, and information dissemination. One objective of CTI is to enhance international collaboration in greenhouse-gas capture and disposal. In December 1997 at Kyoto, Japan, CTI initiated work on a number of practical research and development projects for CO<sub>2</sub> mitigation. Agencies of the governments of the U.S., Japan, and Norway signed an international project agreement in December 1997 (Appendix A) under the Climate Technology Initiative.

The agreement's contents, and the related project scope, resulted from numerous meetings and discussions among international researchers involved in the study of global climate change mitigation technologies for several years. Original signatory agencies were the National Energy Technology Laboratory of the U.S. Department of Energy (formerly, the Federal Energy Technology Center), Japan's New Energy and Industrial Technology Development Organization, and the Norwegian Research Council (NRC). A steering committee, composed of one member per signatory agency, was established to oversee and coordinate projects funded by participating nation-states. The *Ocean Sequestration of CO<sub>2</sub> Field Experiment* is one of those projects.

Technical stewardship of activities initiated by each signatory under the agreement is the responsibility of a second-tier group of organizations or agencies that receive monies from member nation-states. The implementing organizations originally consisted of the Massachusetts Institute of Technology (MIT), Japan's Research Institute of Innovative Technology for the Earth (RITE), and the Norwegian Institute for Water Research (NIVA). A group of scientists and engineers from each of the implementing organizations (known as the Technical Committee) share ideas, cooperatively establish scientific and engineering objectives for activities, and track progress of initiated activities.

In 1999, Natural Resources Canada and a Swiss private company (Asea Brown Boveri) joined the international project agreement. The Canadian Institute of Ocean Sciences (IOS) is the implementing organization for Natural Resources Canada. In 2000, membership in the project agreement was increased to include participation by Australia's Commonwealth Scientific and Industrial Research Organization and by Japan's Central Research Institute of Electric Power Industry, which is the research organization for the electric power industry in Japan.

The Pacific International Center for High Technology Research (PICHTR), a non-profit R&D organization based in Honolulu, Hawai'i, was selected and funded by RITE (Japan) to serve as the general contractor for the *Field Experiment*. PICHTR is responsible for organizing experimental infrastructure, securing permits and authorizations, and providing technical and support services over the duration of the project. In addition, PICHTR has initiated numerous public outreach activities.



## 2.2 PURPOSE OF DOE'S CARBON DIOXIDE SEQUESTRATION PROGRAM

### 2.2.1 DOE'S PURPOSE

The Agreement signed by DOE in December 1997 was established in accordance with DOE's mandate to work in partnership with stakeholders to support development of technologies that could help solve environmental problems related to energy use. The Agreement is part of DOE's ongoing support of research into energy systems.

The main challenges for research on CO<sub>2</sub> sequestration technologies are to reduce the anticipated cost of sequestration, to establish a portfolio of practical sequestration options, and to identify viable options for sequestration that, in the long term, would be effective and would not create new environmental problems. DOE activities related to CO<sub>2</sub> sequestration focus on five research areas (DOE 1997):

- separation and capture at the source;
- sequestration in stable geologic formations;
- sequestration in the ocean;
- sequestration in terrestrial ecosystems; and
- advanced sequestration concepts using chemical, biological, and other innovative approaches.

A sixth area of research addresses systems analysis, which is a critical tool for assessing the effectiveness of alternative strategies. As shown in Table 2-1, ocean sequestration has, by far, the greatest potential of the four research areas related to sequestration (DOE/FETC 1999). As a point of reference, in 1990 global anthropogenic emissions of carbon amounted to 6.0 billion (10<sup>9</sup>) metric tons.

**Table 2-1. Carbon Sequestration Reservoirs**

Carbon sequestration reservoir	Carbon Capacity (in 10 <sup>9</sup> metric tons)
Oceans	1,400 – 2 x 10 <sup>7</sup>
Geologic Structures	300 – 3,200
Terrestrial Systems (forestation and soil)	>100
Fixation or Reuse (advanced concepts)	<i>Unknown</i>
Source: DOE/FETC 1999	

DOE has identified areas where the understanding of the science and technologies related to ocean sequestration needs improvement (DOE/OS 1999). Questions such as the following remain unanswered:

- To what extent would ocean sequestration be effective?
- What would be the best way to engineer a cost-effective and environmentally benign system?
- How would the carbon cycle function in the deep ocean?

DOE's carbon sequestration research has identified a range of activities needed to close information gaps. These activities include laboratory studies, small-scale field experiments, and near-field computer modeling to increase understanding of the behavior of CO<sub>2</sub> released into the ocean. In

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PURPOSE AND NEED FOR AGENCY ACTION

addition, knowledge is needed on the effects of changes in pH and CO<sub>2</sub> concentrations on organisms from mid-water and deep-sea habitats.

### 2.2.2 PROJECT PURPOSE

As conceived, the *Ocean Sequestration of CO<sub>2</sub> Field Experiment* would be conducted at a depth between 2,600 and 3,280 feet (800 – 1,000 meters) and would be focused on key information gaps, as identified in Section 2.2.1. The ocean depth at the center of the N\_wiliwili Dredged Material Disposal Site (approximately 900 meters) is in the middle of that range. The *Field Experiment* would provide data needed to test, validate, and refine existing computer and laboratory models concerning the behavior of liquid CO<sub>2</sub> released into the ocean at moderate depths (2,300-4,900 feet; about 700-1,500 meters).

The specific objectives of the *Field Experiment* are to:

- Investigate CO<sub>2</sub> droplet cloud dynamics;
- Examine pH in the plume and on its margins;
- Clarify effects that hydrates might have on droplet dissolution;
- Trace the evolution of CO<sub>2</sub>-enriched seawater resulting from CO<sub>2</sub> dissolution;
- Assess potential impacts on bacterial biomass, production, and growth efficiency associated with induced changes in seawater pH in the vicinity of the release; and
- Examine the effect of a range of CO<sub>2</sub> injection velocities and injector configurations (e.g., orifice size, number of injectors) on the performance of the system and on physio-chemical effects.

The *Field Experiment* would allow a real-world evaluation of computer model predictions and a refined understanding of the small-scale physics governing the evolution of liquid CO<sub>2</sub> released in the deep ocean. Reliable results obtained from these computer models would represent a very valuable input to the general effort to understand the feasibility and potential consequences of ocean sequestration of CO<sub>2</sub>.

## 2.3 NEED FOR THE ACTION

Global climate change is an issue with many implications for the inhabitants of the planet, and it presents a complex challenge. The potential for climate change, and the response of the nation-states of the world to such change, could dictate fundamental shifts in the methods by which energy is generated and used. In the long-term, options that help to mitigate climate change, such as carbon sequestration, could be essential to preserving or improving the quality of life of the world's inhabitants.

The President's Committee of Advisors on Science and Technology recognized the importance of carbon sequestration research and recommended increasing the U.S. Department of Energy's budget for such research (President's Committee 1997). The Committee also recommended that a larger, science-based sequestration program be developed with a focus on providing a science-based assessment of the prospects and costs of CO<sub>2</sub> sequestration. The Committee recognized that this scientific focus would represent long-term research and development that would not be conducted by industry alone.

Among the opportunities for carbon sequestration are the following:

- Cost-effective CO<sub>2</sub> capture and separation processes;
- Geologic storage;
- Enhancement of natural processes in terrestrial and ocean sinks; and
- Chemical or biological fixation or reuse.

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PURPOSE AND NEED FOR AGENCY ACTION

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Approaches to test technologies in all of the above areas are at an early research stage. As noted in Table 2-1, the world's oceans provide the greatest possible sink for carbon. Additional research is needed to establish answers to critical technical and environmental questions regarding the feasibility, capacity, and long-term viability of enhancing the natural process of CO<sub>2</sub> storage in the ocean. Improved understanding of the basic processes and process chemistries are needed before practical, achievable technology performance and costs can be estimated.

Research is underway in many areas that may lead to lower levels of anthropogenic CO<sub>2</sub> emissions to the atmosphere. One of these areas involves ocean sequestration. Theoretical calculations and laboratory experiments have made significant progress in defining chemical and physical limitations that would constrain any future ocean sequestration scheme (e.g., Wadsley 1995, Shindo *et al.* 1995, Aya 1995, Masutani *et al.* 1995). This work has shown that some key uncertainties cannot be resolved without field experimentation. Tests involving the release of extremely small amounts (i.e., a few kilograms) of CO<sub>2</sub> have helped to confirm and extend theoretical and laboratory results (Brewer *et al.* 2000). However, several scientific questions remain that can only be answered through larger *in situ* releases.

The *Ocean Sequestration of CO<sub>2</sub> Field Experiment* (the "*Field Experiment*") described in this Environmental Assessment has been proposed as a means to expand knowledge of the behavior of CO<sub>2</sub> released into the. It is intended to produce information needed to calibrate and refine predictive models describing the behavior of CO<sub>2</sub> released at a moderate ocean depth appropriate for sequestration. Since release parameters represent a fundamental input to the predictive models, the *Field Experiment* would be best conducted under as wide a range of conditions as can be practically achieved. Key aspects of the release conditions that need to be examined include (1) how the nozzle design will affect the size distribution of droplets, (2) the interactions among droplets near the nozzle, (3) the possibility of hydrate formation, and (4) the potential effects of hydrates, if formed. Many of these have been explored in laboratory experiments, but tests in the open ocean would be needed to verify and extend laboratory results. This would require placing instruments near the nozzle to measure physical and chemical changes induced by the release of the CO<sub>2</sub>, direct observation of CO<sub>2</sub> droplets, and indirect measurements of the CO<sub>2</sub> plume.

In order to achieve the desired objectives (Section 2.2.2), the scale of the *Field Experiment* would need to be sufficient for effective monitoring by available instrumentation. This means the release rates should be in the range of 1.6 to 9.5 gallons per minute (0.1 to 0.6 kilograms per second). The depth of the release would need to be sufficient to allow the CO<sub>2</sub> in the rising droplets to dissolve before reaching the depth at which the CO<sub>2</sub> changes into vapor (approximately 1,375 feet, or 420 meters). In addition, the duration of testing at a defined set of conditions would need to be sufficient to attain a steady state around the discharge nozzle and to provide sufficient additional release time for making meaningful measurements. Computer models predict (see Section 0) that a steady state would be achieved within about thirty minutes, and a minimum of one hour would be needed to take measurements after achieving steady state conditions. Consequently, operational plans call for two-hour release periods, with close monitoring being carried out before, during, and after the release. This chapter provides the application information required by 40 CFR 221.1. The planned release rates and duration are believed to be the minimum that would achieve the experimental objectives. In this regard, it is worth noting that the maximum release rate that is now proposed is 40 percent lower than the 1.0 kilograms per second rate scientists originally thought would be needed. The reduction in maximum flow rate raises the level of uncertainty that the goals will be achieved but it further limits the volume of water that would be affected.

DESCRIPTION OF THE PROPOSED ACTION

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## 3.0 DESCRIPTION OF THE PROPOSED ACTION

### 3.1 INTRODUCTION

The proposed *Field Experiment* would be conducted under the auspices of the Pacific International Center for High Technology Research (PICHTR)<sup>1</sup>. This chapter provides a detailed description of the way the *Field Experiment* would be conducted. Section 3.2 identifies the basic equipment that would be employed and the types of activities that would occur during the *Field Experiment*, and Section 3.3 describes the sequence of events anticipated during the *Field Experiment*. The termination phase of the *Field Experiment*, during which the at-sea release system and the monitoring systems would be removed from the ocean, are described in Section 3.4.

### 3.2 PROPOSED EQUIPMENT AND MATERIALS

The equipment needed to conduct a vessel-based *Field Experiment* would be mounted on, and deployed from, ocean-going vessels chartered for the purpose. Figure 3-1 schematically illustrates the overall configuration of the experiment, which has been specifically tailored to the scale, duration, and scientific purpose of the proposed *Field Experiment*. Figure 3-2 is a diagram of the type of vessel most likely to be used.<sup>2</sup>

The proposed *Field Experiment* involves the release of pure liquid CO<sub>2</sub> purchased expressly for the purpose. The CO<sub>2</sub> would be purchased from local suppliers. It would be identical to the CO<sub>2</sub> that is used by bottlers in the manufacture of carbonated beverages for human consumption.

#### 3.2.1 CARBON DIOXIDE DELIVERY VESSEL

One vessel would carry the equipment used to release the liquid CO<sub>2</sub>. This vessel would have good positioning capabilities, which means that it would have navigational and mechanical equipment needed to remain in a fixed position without use of an anchor. The equipment mounted on the vessel would consist of the following:

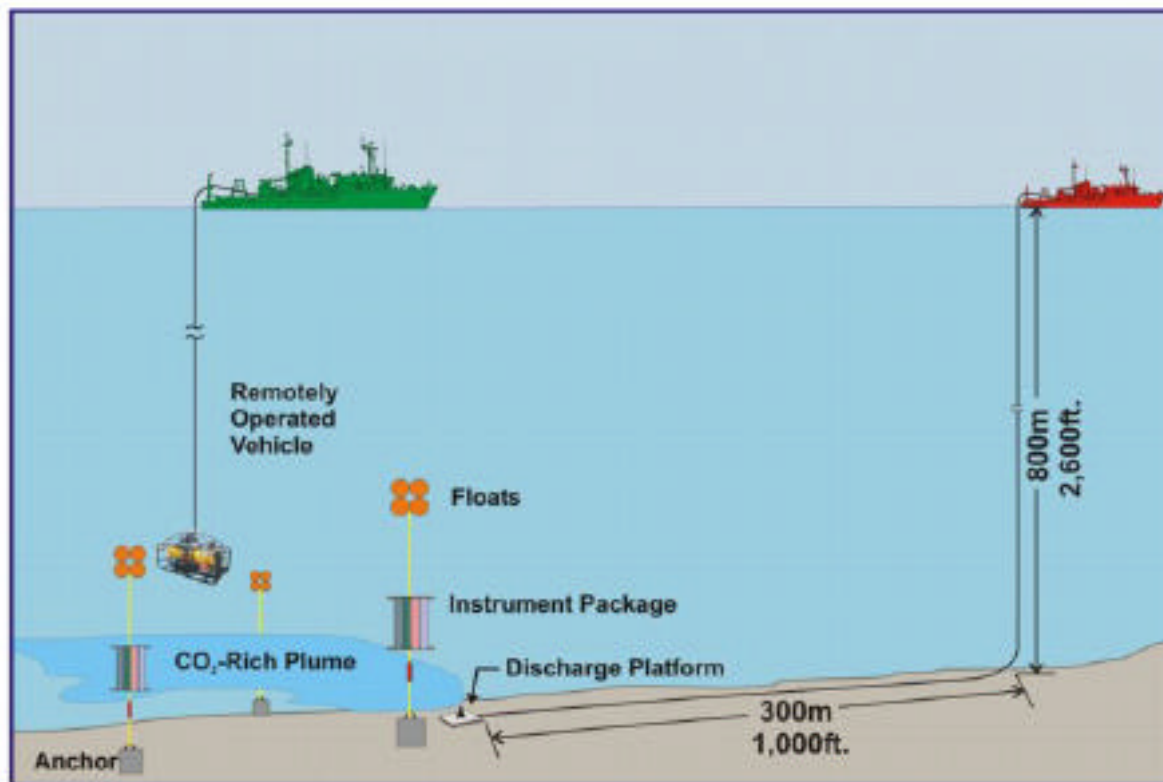
- A standard refrigerated CO<sub>2</sub> storage tank system of the type widely used by food and beverage companies and hospitals. The deck-mounted tank would keep the CO<sub>2</sub> at a pressure of 20 to 22 bars and -4°F (about -20°C).
- A pump, metering system, and high-pressure hose capable of delivering the liquid CO<sub>2</sub> from the storage tank into tubing through which the CO<sub>2</sub> would be transported to the discharge platform and nozzle on the seafloor.
- A reel holding approximately 3,940 feet (1,200 meters) of 1.5- to 2-inch (3.81 to 5.08 centimeter) outside diameter, coiled tubing,<sup>3</sup> a control cabin with hydraulic power pack, and a deck-mounted container housing controls for the other equipment.

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<sup>1</sup> Attention Mr. Keith Matsumoto, Acting President and Chief Executive Officer Building 5, Bay 14, 1020 Auahi Street, Honolulu, Hawaii 96814

<sup>2</sup> The experiment could use vessels already based in Hawaiian waters or ones whose schedule would bring them through Hawai'i during the expected time window for the experiment. The choice would depend upon vessel availability and cost. Because of this, a detailed description cannot be provided at this time.

<sup>3</sup> The leading candidate would be a product manufactured for offshore oil and gas applications. The continuous, coiled tubing would be fabricated from alloy steel. All tubing would be tested at pressures greater than or equal to 6,000 pounds per square inch (414 bar) before shipment. Since the planned operating CO<sub>2</sub> pressures would be less than or equal to 80 bar, the safety factor would be greater than 5.



**General Methods Used in the Field Experiment**

Prepared For:

Pacific International Center for  
High Technology Research  
(PICHTR)

Prepared By:



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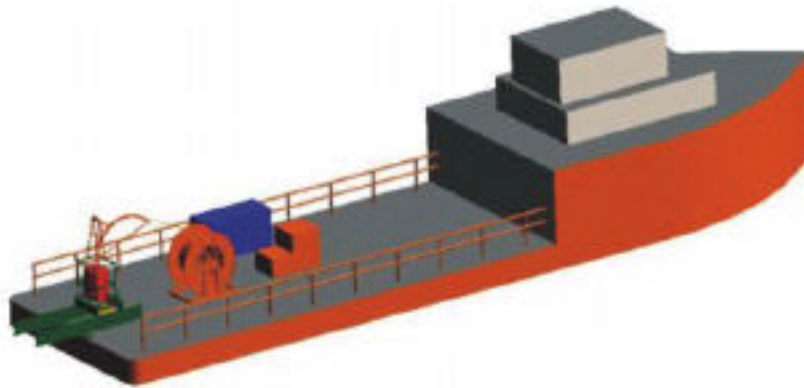
Planning Solutions, Inc.

Figure 3-1:

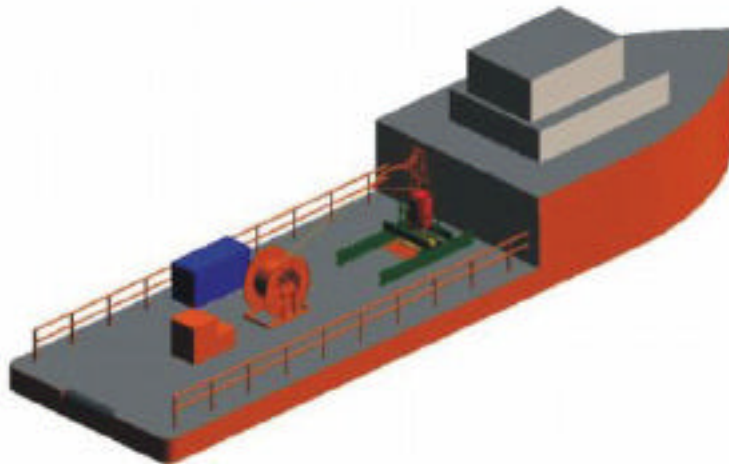
**General Methods Used  
In the Field Experiment**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

### Vessel With No Moonpool



### Vessel With Moonpool



Prepared For:  
Pacific International Center for High  
Technology Research (PIC-CTR)

Prepared By:



Source:  
J.M. Consult

Figure 3-2:

### Typical Vessel and Deck Mounted Equipment

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

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**DESCRIPTION OF THE PROPOSED ACTION**

- A pump, metering system, and high-pressure hose capable of delivering the liquid CO<sub>2</sub> from the storage tank into tubing through which the CO<sub>2</sub> would be transported to the discharge platform and nozzle on the seafloor.
- A reel holding approximately 3,940 feet (1,200 meters) of 1.5- to 2-inch (3.81 to 5.08 centimeter) outside diameter, coiled tubing,<sup>4</sup> a control cabin with hydraulic power pack, and a deck-mounted container housing controls for the other equipment.

A discharge platform, similar to one shown in Figure 3-3 would be carried on the deck of the ship. When the vessel is in position for deployment, a test nozzle would be fitted to the end of the outlet pipe, and the inlet pipe would be connected to the end of the coiled tubing. The platform would then be lowered to the bottom at a depth between 2,600 and 3,280 feet (800 – 1,000 meters). The platform would be about six or seven feet wide by thirteen feet long (2 meters by 4 meters) and would weigh approximately 11,000 pounds (5 metric tons). The discharge platform would consist of the following:

- A flat, steel structure that would provide sufficient tension to the tubing during deployment to minimize drifting due to currents.
- A vertical steel pipe connected to the CO<sub>2</sub> supply tubing by a short, flexible hose secured by chains. The connection would also include a swivel joint to minimize torsion forces in the tubing.
- A trumpet-shaped guide to prevent kinking in the CO<sub>2</sub> supply line.
- Four pointed, steel legs to minimize horizontal movements on the hard seabed, which can have a slope of as much as 30 degrees.
- A discharge pipe to which the test nozzle would be attached; the discharge pipe would extend outward and upward from the side of the platform.
- Anti-backflow devices, such as a check valve, to prevent seawater from entering the pipe and causing hydrate blockages.

The platform may also be equipped with electric heaters to 'melt' any hydrates that form, transponders, and other small pieces of scientific equipment.

**3.2.2 OTHER SUPPORT VESSELS**

Other vessels would be used to support the *Field Experiment*. These would include up to two mother ships for the remotely operated vehicles (ROVs) or submersibles that would be used to collect data during experimental tests (see Figure 3-4). In addition, a small boat would probably be chartered to carry scientists and samples between the research vessels and the shore. Small chemical and physical sensors, as well as ROV transponders, would be placed temporarily on the seafloor during the *Field Experiment*.

**3.3 PROPOSED TEST SEQUENCE**

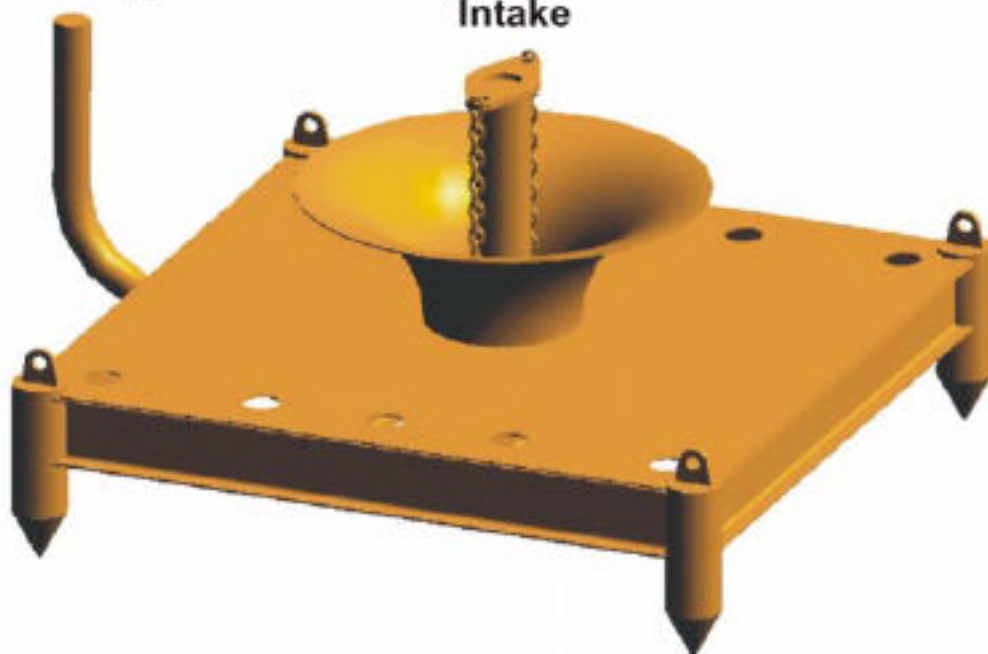
The *Field Experiment* would consist of a series of test sequences, with each individual test designed to observe and evaluate the behavior of liquid CO<sub>2</sub> in seawater as release parameters vary under known physical conditions. Since nozzle design would influence the initial characteristics of the CO<sub>2</sub> droplets for a given release rate, varied nozzle designs would be used to widen the range of practical release parameters.

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<sup>4</sup> The leading candidate would be a product manufactured for offshore oil and gas applications. The continuous, coiled tubing would be fabricated from alloy steel. All tubing would be tested at pressures greater than or equal to 6,000 pounds per square inch (414 bar) before shipment. Since the planned operating CO<sub>2</sub> pressures would be less than or equal to 80 bar, the safety factor would be greater than 5.

**Discharge**

**Intake**



**Prepared For:**

Pacific International Center for High  
Technology Research (PICHTR)

**Prepared By:**



**Source:**

J.M. Consult

Figure 3-3:

**Discharge Platform**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment





**Oblique View**



**Front View**

**Prepared For:**

Pacific International Center for High  
Technology Research (PICHTR)

**Prepared By:**



**Source:**

Mitsui Engineering and Shipbuilding  
Akishima Laboratory, Tokyo, Japan

**Figure 3-4:**

**Type of ROV Used for  
Monitoring in the  
Field Experiment**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

**DESCRIPTION OF THE PROPOSED ACTION**

Table 3-1 summarizes the most important characteristics of the planned tests. A total of up to 20 metric tons of liquid CO<sub>2</sub> would be released over a period of approximately two weeks. The releases would occur as part of a series of tests, none lasting more than 2 hours.

**Table 3-1. Preliminary *Field Experiment* Matrix**

Duration of Each Test Release (approximate)	Two Hours
CO <sub>2</sub> Flow Rates	1.6 and 9.5 gallons per minute (0.1 and 0.6 kg/s)
Number of Nozzle Designs Tested	2
Ambient Conditions	Conduct tests at range of current speeds, if possible
Number of Tests	12 to 20
Total Amount of CO <sub>2</sub> Released	Approximately 5,000 gallons (20 metric tons)
Source: Pacific International Center for High Technology Research (PICHTR)	

A draft experimental plan for the *Field Experiment*, which includes more detailed descriptions of the anticipated experimental and monitoring activities, schedule, and contingency provisions, is presented in Appendix C. This plan was formulated through collaboration among the principal scientists in charge of the experiment and professional biological oceanographers with extensive experience investigating the marine ecosystems of the Hawaiian Islands. The *Field Experiment*, because of its planned short duration and low release rates of CO<sub>2</sub>, would not provide adequate foundation for a comprehensive investigation of environmental impacts. However, some preliminary studies directed toward evaluating how some biota might respond to the releases are planned (see Section 4.3.2.1.1).

Tests would only be conducted when weather and sea conditions allow vessels to maintain their positions within a designated area. Based on equipment requirements, the preferred surface current for conducting tests would be 2 knots (about 1 meter per second) or less.

The vessel deploying the platform would maintain station while the coiled tubing would be extended for a single experimental test series. In general, this means that the vessel would be stationary above the platform for periods ranging from 8 hours to several days. Radioactive substances would not be used in any of the experiments.

### 3.3.1 DEPLOYMENT

Before the discharge platform would be lowered from the ship, one of the specially designed nozzles would be attached to the end of the CO<sub>2</sub> discharge pipe. Each nozzle would likely consist of a vertical riser (pipe) about 8 inches (20 centimeters) in diameter that ends in a blind flange with 10 to 60 small holes for release ports.

When prepared for deployment, the platform and attached coiled tubing would be slowly lowered into the water. The weight of the platform would result in a virtually vertical descent of the assembly.<sup>5</sup>

<sup>5</sup> Given the typical differences between surface and bottom currents, the maximum deflection in the tubing would be approximately 10 feet (3 meters) over the 2,600-foot (800 meter) length of tubing between the surface and the discharge platform.

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**DESCRIPTION OF THE PROPOSED ACTION**

While deploying the platform, the ship would maintain station within a radius of approximately 80 feet (25 meters) over the platform's intended resting-place on the bottom. After the platform reaches the bottom, additional tubing would be deployed until approximately 650 to 1,000 feet (200 to 300 meters) of tubing would be laid on the seafloor. Laying out this additional tubing would provide an unobstructed space immediately above the discharge platform so that observers would have a clear view of the CO<sub>2</sub> plume. In addition, the ROVs or submersibles would be able to maintain a safe separation from the vertical segment of the tubing.<sup>6</sup>

The platform would be retrieved from the seafloor to change the discharge nozzle, perform maintenance on the nozzle or discharge platform instrumentation, or correct any operational problems. A maximum of 10 deployments of the discharge platform would be anticipated, but the most likely number of deployments would be fewer than half that amount.

**3.3.2 CARBON DIOXIDE RELEASE**

Following proper placement of the discharge platform on the bottom, the CO<sub>2</sub> release through the nozzle being tested would begin. The design of each nozzle would generate a unique assemblage of CO<sub>2</sub> droplets at each release rate. As indicated in Table 3-1, the CO<sub>2</sub> would be released from the nozzle at flow rates ranging from about 1.6 gallons per minute (0.1 kilograms per second) to 9.5 gallons per minute (0.6 kilograms per second). Typically, each test sequence would be conducted over the course of a few days. However, unusual weather or other factors could prolong the duration of a test sequence.

Following each release, two distinct regimes of CO<sub>2</sub> behavior would result. The first regime would consist of rising droplets of liquid CO<sub>2</sub>. The release rate and the design of the nozzle would largely control both the size and shape of the droplets. The planned flow regimes and nozzle designs would be established to control the formation of "slush."<sup>7</sup>

The second regime would result as the buoyant droplets rise after being released from the injection nozzle. The droplets would dissolve in seawater, because the natural concentration of inorganic carbon in ambient seawater is orders of magnitude below the solubility limit for liquid CO<sub>2</sub>. As discussed in more detail below, at the release rates planned for the *Field Experiment*, the vertical rise of the liquid CO<sub>2</sub> droplets would cease within 1,000 feet (~300 meters) from the nozzle.

The dynamics of the ascending droplets would be complex, with some seawater being entrained upward by the momentum of the rising droplets. CO<sub>2</sub>-enriched water along the edges of the rising plume would sink as dissolved concentrations of carbon in it increase. This relatively dense, carbon-rich seawater would stop sinking when sufficient mixing with lighter ambient seawater would bring the mixture to a neutrally buoyant equilibrium. Then, the carbon-rich water would drift with the current while being diluted further by turbulence. The predicted behavior of the discharge plume is discussed in Section 0.

**3.3.3 MONITORING**

During each test, staff on the vessel deploying the platform would: operate and monitor the CO<sub>2</sub> pump system and nozzle flow rate; maintain the vessel's position; and interface with project administrators and the ships from which the ROVs would operate.

The crew and staff of the vessel or vessels deploying the survey systems would: make ocean measurements; control and monitor the system location, provide feedback concerning the behavior of the release and the condition of the discharge platform; visually monitor the behavior of megafauna near the test release; and conduct related tests and measurements. Sampling bottles would be deployed and retrieved from the research vessels to collect water and sediment for chemical and biological (bacterial) analysis. Conductivity, temperature, and depth (CTD) measurements from the research vessel would

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<sup>6</sup> ROVs or submersibles would collect data during the *Field Experiment*. The vessel deploying the platform would not remain directly overhead while these instrument systems are operated to avoid the possibility of becoming entangled with the tubing or cables or collision with the ship itself.

<sup>7</sup> Slush in this context is an ice-like mixture of seawater and CO<sub>2</sub> where the two are bonded closely together.

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**DESCRIPTION OF THE PROPOSED ACTION**

supplement the data obtained from small sensors moored temporarily on the bottom and from the mobile survey systems (ROVs and submersible).

The CO<sub>2</sub> droplets would be visible and tracked directly using video equipment. Dissolved carbon in the carbon-rich water plume would not be visible and would need to be monitored indirectly. Since CO<sub>2</sub> would increase acidity (lower the pH) of the seawater as it dissolves, the plume would be distinguished from normal seawater by measuring the pH. Non-toxic tracers, such as fluorescent dyes, might be added to the CO<sub>2</sub> to facilitate optical monitoring.

Instruments mounted on mobile survey systems and instrument arrays moored temporarily on the seafloor would be used to monitor ambient conditions. The ROV instrument package would probably include video, conventional salinity, temperature, and pH probes. The instrument package might also include a modified Acoustic Doppler Velocity meter (ADV).

Data collected during each test would be used to produce detailed maps of the parameters under scientific investigation (e.g., pH, temperature, and salinity) and of the current fields. The mobile video systems and video lamps would provide flow images of the CO<sub>2</sub> droplet evolution over time. The ADV would obtain point measurements of fluid velocities for use in evaluating turbulence within the discharge plume. Small transponders on the seafloor would be used to track the underwater position of the mobile systems.

Data obtained on CO<sub>2</sub> droplet cloud dynamics, effects of hydrate films on droplet dissolution, and three-dimensional mapping of the dispersing, CO<sub>2</sub>-enriched seawater would be used to assess the physical and chemical effects of CO<sub>2</sub> sequestration in ocean water.

To assess potential impacts of CO<sub>2</sub> sequestration on environmental health, variations in bacterial biomass, productivity, and growth efficiency would be determined and compared to water column pH. Measurement of nutrients (dissolved and particulate organic carbon and organic nitrogen) would be conducted for corollary analyses. These measurements would identify changes in substrate availability that could alter bacterial activity during injection of CO<sub>2</sub>. The analyses of bacterial cycling rates would be combined with an analysis of the variation in bacterial genetic diversity to interpret stresses that might arise from pH changes. This information would provide a better understanding of the effect of water column acidification on the lowest levels of marine food chains.

**3.3.4 LOGISTICAL SUPPORT**

One of the advantages of a vessel-based experiment would be that the vessels provide portable operations platforms. The specific types of required logistical facilities needed to support the vessels would depend on the location of the experiment and on the specific research vessels that would be used. However, the differences between conducting a vessel-based *Field Experiment* at different ocean sites would be minor.

**3.4 POST TEST/SITE CLEAN-UP**

Because of the deployment method planned, the discharge platform, nozzle, and tubing would be removed from the seabed as soon as the test releases are completed. The small instrument packages and transponders that would be deployed around the test area would also be retrieved.

**3.5 COMPARISON OF ALTERNATIVES**

Table 3-2 compares potential environmental effects of the Vessel-Based *Field Experiment* at the N\_wiliwili Disposal Site to the No Action Alternative.

## DESCRIPTION OF THE PROPOSED ACTION

Table 3-2 Anticipated Impacts

<b>RESOURCE AFFECTED</b>	<b><i>FIELD EXPERIMENT</i> N_wiliwili Disposal Site</b>	<b>NO ACTION</b>
<b>Marine Water Quality</b>	Cloud of liquid CO <sub>2</sub> droplets up to 1,000 feet from discharge nozzle; temporary depression of pH	No or similar effects
<b>Seafloor</b>	Local abrasion of surface due to platform and pipe emplacement and movement.	No or similar effects
<b>Benthic Marine Life</b>	Potential for stress and mortality on benthic life immediately beneath discharge platform & pipeline and in areas subject to pH below 6.5	No or similar effects
<b>Deep-Water Pelagic Marine Life</b>	Very small loss of plankton and minor effects on mobile organism communities	No or similar effects
<b>Midwater Marine Life</b>	Very minor stress on local plankton populations	No or similar effects
<b>Surface-Water Marine Life</b>	No adverse effects	No or similar effects
<b>Historical and Cultural Resources</b>	No effects on archaeological or historic sites.	No or similar effects
<b>Air Quality and Climate</b>	Emissions from engine exhaust. Experiment would help improve models used to evaluate climate change.	No or similar effects
<b>Noise</b>	No adverse effects	No or similar effects
<b>Marine Transportation</b>	Slightly increased vessel traffic for short periods during two-week experiment; some limits on vessel movement.	No or similar effects
<b>Land Use</b>	No effects	No effects
<b>Aesthetic Resources</b>	No effects	No effects
<b>Socioeconomic Resources</b>	Inputs of goods and services to Hawai'i communities; expenditures for goods where test equipment would be manufactured.	No or similar effects
<b>Public Facilities and Services</b>	No effects	No effects
<b>Public Safety &amp; Health</b>	No effects	No effects

## 4.0 AFFECTED ENVIRONMENT & ENVIRONMENTAL CONSEQUENCES

This chapter discusses effects of conducting the proposed Ocean Sequestration of CO<sub>2</sub> *Field Experiment* at the N\_wiliwili Ocean Disposal Site. Section 4.1 contains an overview of the most relevant features of the environments that might be affected. Sections 4.2 through 4.13 discuss anticipated environmental impacts on natural and human resources. Section 4.14 discusses Environmental Justice issues as required by Executive Order 12898. Section 4.15 summarizes pollution prevention measures that would be employed.

The discussion concentrates on the key resources that have the potential to be affected by the *Field Experiment*. These include ocean water quality, benthic and pelagic biota, traditional cultural resources, and recreational and commercial uses of the ocean waters near the experiment. Factors likely to be affected to a lesser degree by the proposed activities are discussed in less detail. These include ocean navigation while the experiment is underway, health and safety, and historic and cultural sites. The analysis considers both normal operation and possible accident scenarios.

### 4.1 OVERVIEW OF THE AFFECTED ENVIRONMENT

The N\_wiliwili Ocean Disposal Site is the only EPA-designated ocean dumping site within the correct depth range for the *Field Experiment*. Its location, depicted in Figure 4-1, is at 21° 55'N, 159° 17' W. The site is a circle centered on these coordinates and with a radius of 1,000 meters (3,280 feet). This site is approximately 4 nautical miles from N\_wiliwili Harbor, Kaua'i, Hawai'i.

#### 4.1.1 SEABED CHARACTERISTICS

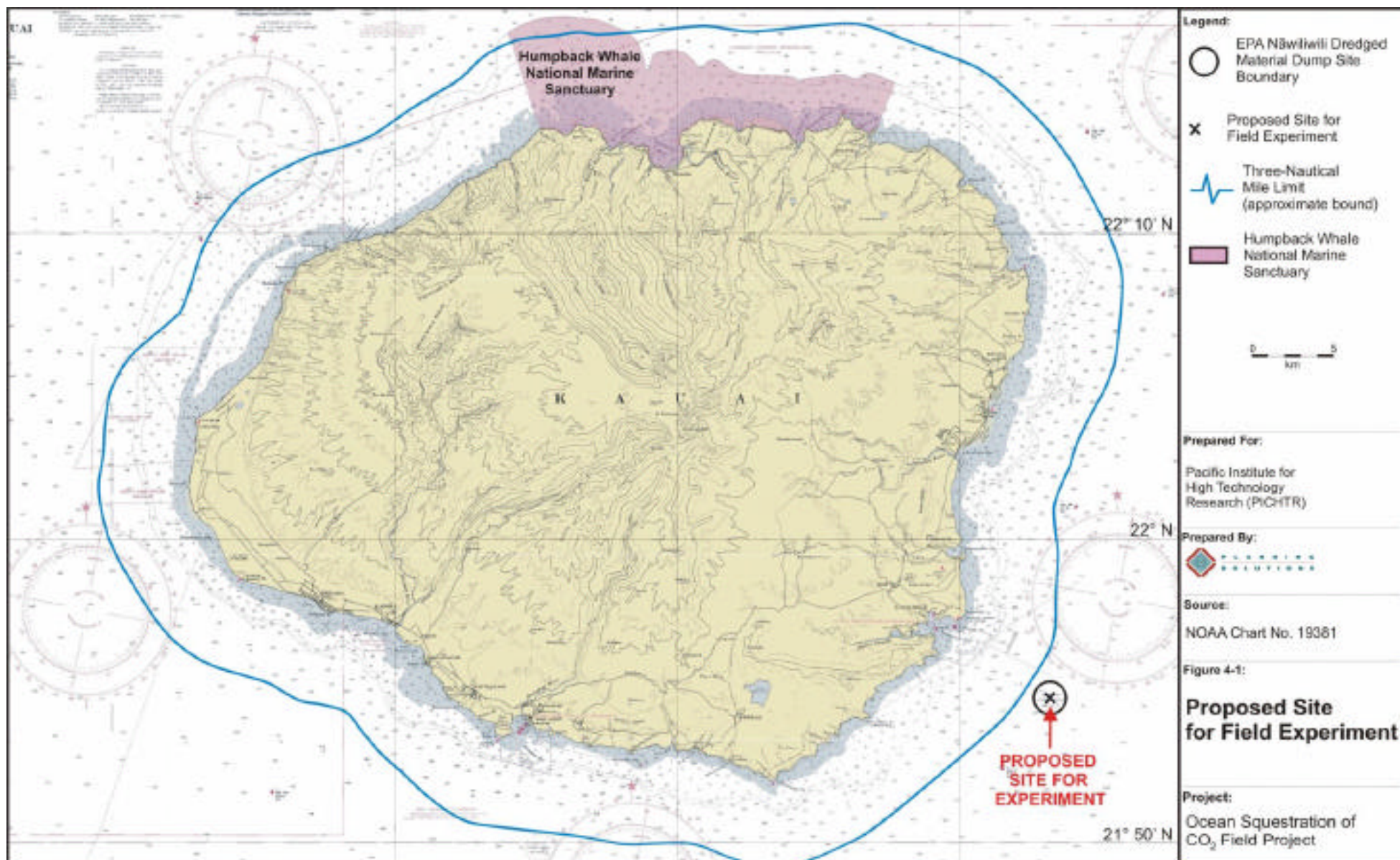
Figure 4-2 shows the bathymetric contours at the N\_wiliwili Disposal Site. The seafloor slopes gently from the northwest to the southeast, roughly parallel to the island shoreline. The average slope across the northwestern portion of the area is approximately 7°, and it drops more steeply at an angle of up to 17° in the southeastern portion. The sediment collected in this area during the U.S. Army Corps of Engineers investigations for its suitability as a dumpsite (COE 1977a) consisted of coarse, silty sand composed of 11.4% basalt grains and 73.6% carbonates. The sediments were moderately sorted within the size range measured, but lacked significant clay-sized materials. Cores could not be recovered, perhaps because the sediments are thin and underlain by hard substrate. Grab samplers were used to collect the samples.

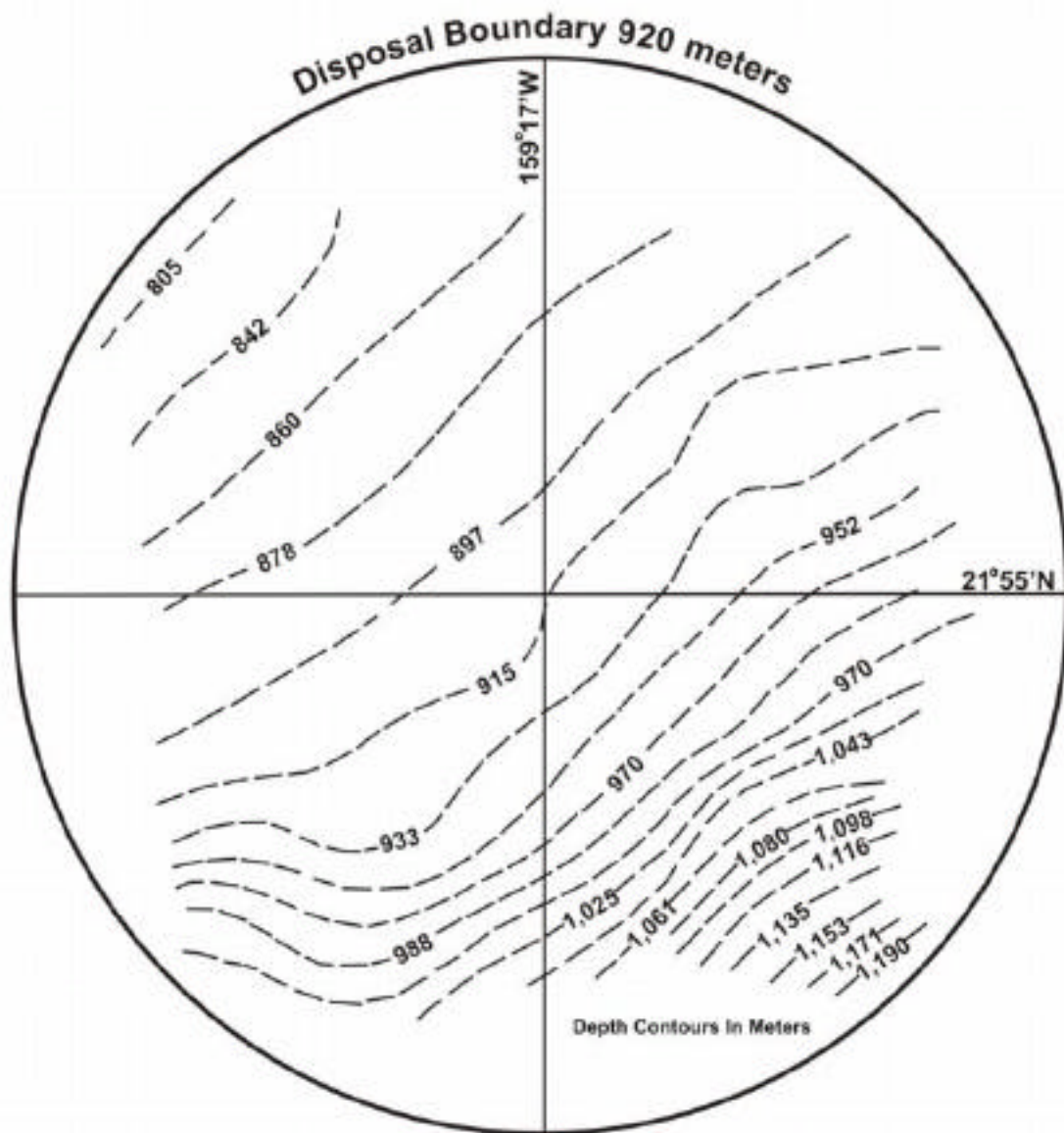
#### 4.1.2 GENERAL OCEANOGRAPHIC CONDITIONS & MARINE WATER QUALITY

Eight vertical profiles of nutrient and other seawater variables taken in the vicinity of the Disposal Site (average distance from Disposal Site, 16.5 km; minimum 6; maximum 22.6) are shown in Figure 4-3 (NODC 2001a). The water column is typical of the tropical Pacific Ocean, with low levels of nutrients, particularly in surface waters. There is a clearly stratified water column with a well-developed thermocline.


Vertical profiles of temperature and salinity were also collected as part of the Corps of Engineers study of the site (COE 1977b). These profiles are very similar to those represented in the NODC database. The temperature profile from the Corps study shows the same well-developed thermocline between approximately 100 – 500 m water depths and a temperature at the 800 to 1,000 m depth of about 4° C. The Corps study also shows a salinity profile with a maximum level at about 150 m and slowly dropping salinity below a depth of about 750 m. The Corps-measured levels of salinity are slightly higher than those in the NODC database (NODC maximum ~35.3 parts per thousand [ppt]; Corps maximum ~36.5 ppt).







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 **PLANNING  
SOLUTIONS**

Source:  
COE (1977b)

Legend:

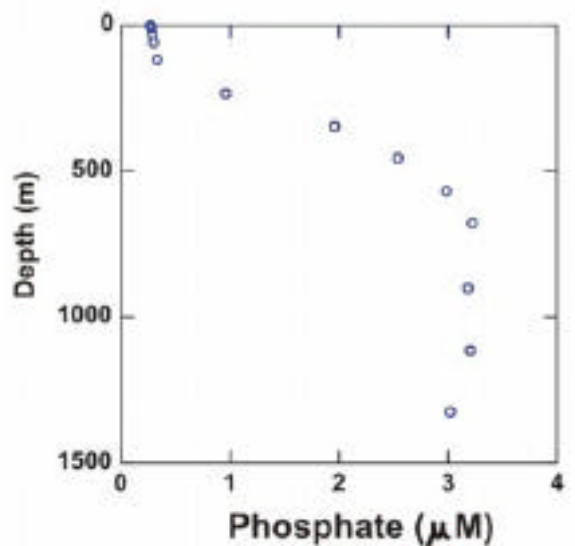
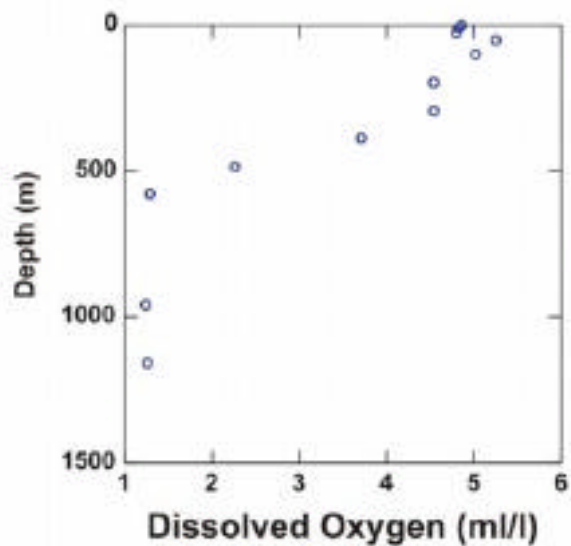
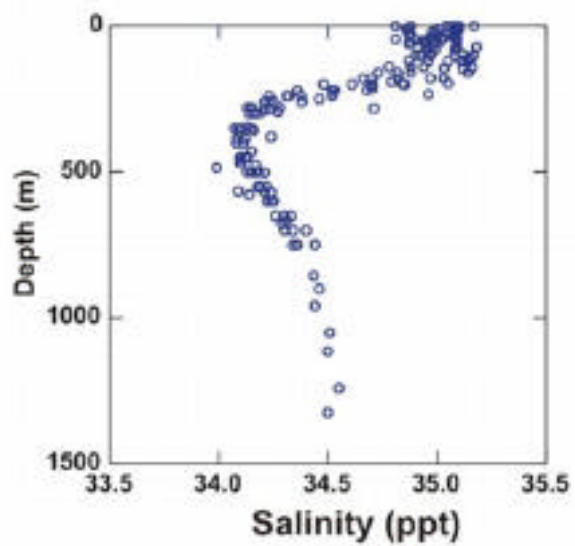
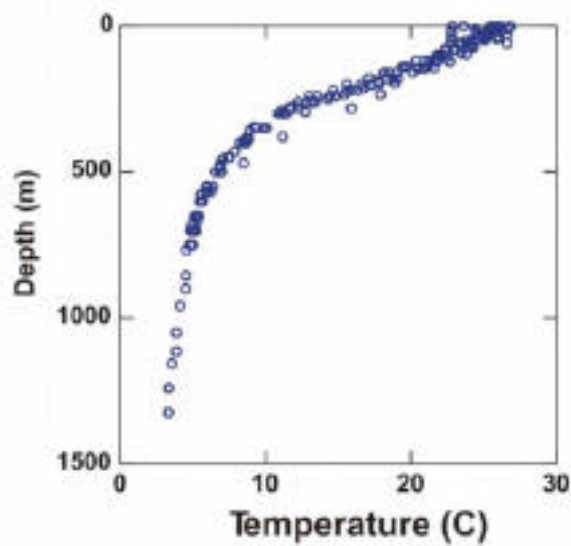


Figure 4-2:

### Bathymetry of the Nawiliwili Dredged Material Disposal Site

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment





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Source:  
NOOC (2000a)

Figure 4-3:  
**General Oceanographic  
Variables of the  
Nawiliwili Dredged  
Material Site**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

#### 4.1.3 OCEAN CURRENTS

Surface current profiles extending to water depths of about 300 m (1,000 feet) have been collected in the vicinity of the N\_wiliwili Ocean Disposal Site by passing research vessels equipped with Acoustic Doppler Current Profilers (ADCP) and modern Global Positioning System (GPS). These current data have been archived by the National Oceanographic Data Center (NODC) in collaboration with the Firing Acoustic Doppler Current Profiler Laboratory at the University of Hawai'i (NODCb).

Current data from this set, collected on six different oceanographic expeditions that traversed within 30 nautical miles of the Disposal Site (NODC records 27, 119, 139, 141, 192, and 193) were retrieved for this study. Figure 4-4 summarizes the results. Ship-based ADCP profilers are capable of obtaining data from depths of up to 300 meters. The deep extreme of the profiler data, 260 m (850 feet) indicates average current speeds of 14 cm/s (0.3 knots). At the shallow extreme of the profiler data, 30 – 40 m (98 – 130 feet) average current speeds of 25 cm/s (0.5 knots) and maximum speeds of 70 cm/s (1.4 knots) have been observed at the Disposal Site. The deep extreme of the profiler data, 260 m (850 feet) indicates average current speeds of 14 cm/s (0.3 knots).

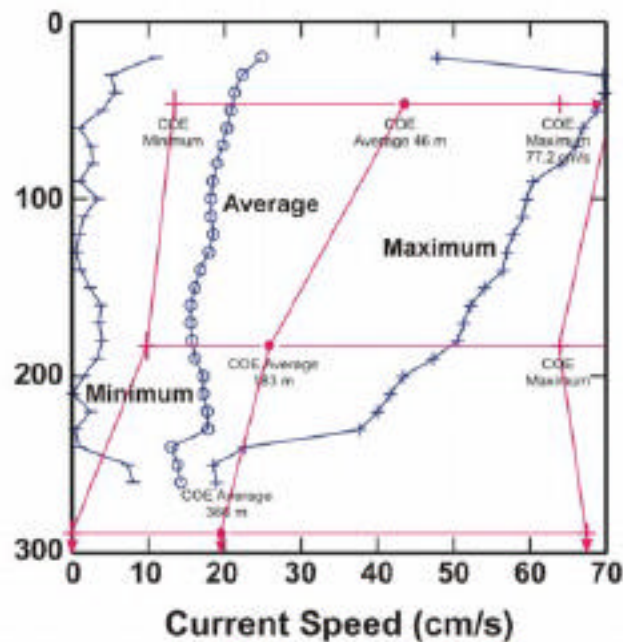
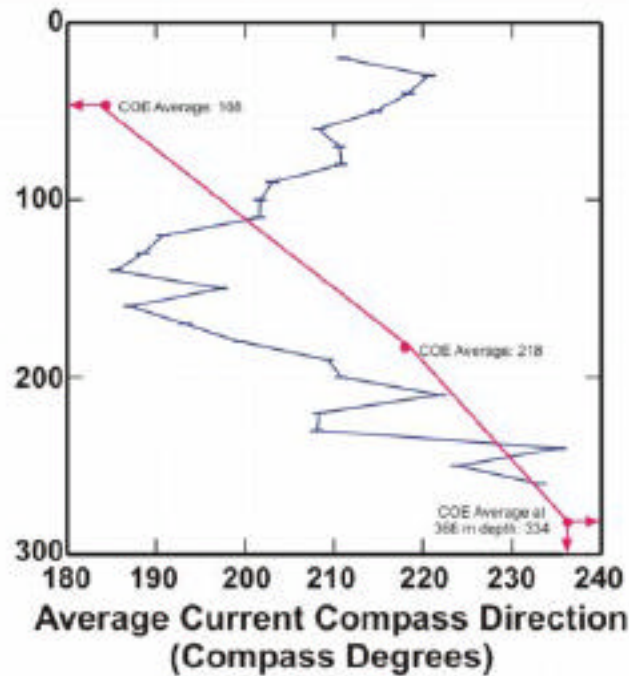
The Corps of Engineers study (COE 1977b) measured currents at the N\_wiliwili Disposal Site for approximately 18 hours (October 22-23, 1976), using current meters deployed at 150, 600 and 1,200 feet (respectively, 46, 183, and 366 m). The minima, averages, and maxima from these data collections are presented also in Figure 4-4. The currents measured during the one-day deployment were somewhat faster currents than those measured with the profiling systems. The maximum level of 67.5 cm/s (1.31 knots) measured at the 1,200 ft (366 m) deployment is somewhat suspect, however, since it occurred only in the first hour of the deployment and is almost twice as high as the next highest measurement. It is possible that this represents a transient anomaly associated with the deployment operation.

All of the data reported above are from depths well above the 900 meter depth at which the proposed experimental release would occur. Current speeds decrease with increasing depth, and data collected elsewhere in Hawai'i and the world indicate that the current speed at depths equal to the release depth and the shallowest depth to which the CO<sub>2</sub>-enriched plume or liquid CO<sub>2</sub> droplets would rise is only a small fraction of that speed.

#### 4.1.4 SPECIES OF PARTICULAR CONCERN

Species of particular concern at the N\_wiliwili Ocean Disposal Site include the following marine turtles and marine mammals. An asterisk denotes a species listed by the U.S. Fish and Wildlife Service as threatened or endangered.

- Green turtle (*Chelonia mydas agassizii*)\*
- Pacific Hawksbill turtle (*Eretmochelys imbricata bissa*)\*
- Olive Ridley turtle (*Lepidochelys olivacea*)\*
- Loggerhead turtle (*Caretta caretta*)\*
- Leatherback turtle (*Dermochelys coriacea schlegelii*)\*
- Hawaiian Monk Seal (*Monachus schauinslandi*)\*
- Humpback whale (*Megaptera novaeangliae*)\*
- Finback whale (*Balaenoptera physalus*)\*
- Blue whale (*Balaenoptera musculus*)\*
- Bryde's whale (*Balaenoptera edeni*)
- Right whale (*Eubalaena glacialis*)\*
- Sperm whale (*Physeter macrocephalus*)\*
- Sei whale (*Balaenoptera borealis*)\*
- Spinner dolphins (*Stenella longirostris*)
- Spotted dolphins (*Stenella attenuata*)
- Rough-toothed dolphin (*Steno bredanensis*)



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Source:

COE (1977b)  
NODC (2000b)

- NODC Averages
- Army Corps of Engineers Averages

Figure 4-4:

**Ocean Current Direction  
and Speed Near the  
Nawiliwili Disposal Site**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

- Bottlenose dolphin (*Tursiops truncatus*)
- Striped dolphin (*Stenella coeruleoalba*)
- Risso's dolphin (*Grampus griseus*)
- Melon-head whale (*Peponocephala electra*)
- Pygmy killer whale (*Feresa attenuata*)
- False killer whale (*Pseudorca crassidens*)
- Short-finned pilot whale (*Globicephala macrorhynchus*)
- Killer whale (*Orcinus orca*)
- Pygmy sperm whale (*Kogia breviceps*)
- Dwarf sperm whale (*Kogia simus*)
- Cuvier's beaked whale (*Ziphius cavirostris*)
- Blainville's beaked whale (*Mesoplodon densirostris*)

The threatened Newells' shearwater (*Puffinis auricularis*), and the endangered dark-rumped petrel (*Pterodroma phaeopygia sandwichensis*) may also forage in the project area.

Species of concern to the sport-fishing community include representatives from several families including (but not limited to) snappers (*Lutjanidae*), pomfrets (*Bramidae*), jacks (*Carangidae*), dolphins (*Coryphaenidae*), mackerels and tunas (*Scombridae*), swordfishes (*Xiphiidae*), and billfishes (*Istiophoridae*). In 1997, about 303,000 pounds of fish from the Anahola-N\_wiliwili offshore area were sold, a modest amount by island standards.

N\_wiliwili Disposal Site is far from the Hawaiian Islands Humpback Whale National Marine Sanctuary. On Kaua'i, the Whale Sanctuary is established only on the north shore of the island. Because of the geographic location of the N\_wiliwili Ocean Disposal Site, and the small magnitude and the great depth to which project-related water quality changes would be limited, no substantial impacts on species of concern would be expected from the *Field Experiment*.

#### 4.1.4.1 Seafloor Marine Life (Depth range: 650 to 6,000 feet; ~200–1,900 meters)

The center of the N\_wiliwili Disposal Site where the platform would be placed has a relatively flat, unremarkable, sediment-covered seafloor. During the biological surveys conducted for the U.S. Army Corps of Engineers (COE 1977a, COE 1977b), many of the sediment areas showed evidence of bioturbation in the form of sediment mounds and pits. Assemblages of Foraminifera, micro-mollusks, and mobile megafauna captured in trawls appear to be typical of the Hawaiian slope fauna at these depths. Factors that are important for the kinds of activities that are planned as part of the *Field Experiment* include the following:

- Organisms living within the sediments are isolated from the CO<sub>2</sub> plume by the restricted pore water circulation at the study depths. Moreover, sediments at the site contain high concentrations of calcium carbonate (from corals, mollusks, coralline algae, etc.), which would act to buffer any excess acidity if the plume manages to infiltrate into the pore water.
- Furthermore, organisms that sense perturbations such as those associated with the experimental release and sense these as an irritant often respond by burrowing more deeply into the sediment, away from the source of irritation.
- Organisms living in soft sediments are less susceptible to harm by movements of the CO<sub>2</sub> supply pipe than are organisms that are attached to hard substrate.
- Soft sediments constitute the most abundant benthic habitat within the potentially impacted depth range in the Hawaiian Islands. Thus, any disruption to the benthos that does occur during the conduct of the *Field Experiment* would affect organisms in the most common taxonomic groups, and only a very small percentage of their total population and species ranges. Corals or other encrusting megafauna are generally not found in sedimentary habitats.

## AFFECTED ENVIRONMENT &amp; ENVIRONMENTAL CONSEQUENCES

Commercially and recreationally exploited species living and feeding on the seafloor at this depth potentially include the following:

- The deep-water shrimp, *Heterocarpus laevigatus*, with a depth range of 1,500 to 3,000 feet (about 450-900 meters, King 1987, Tagami and Ralston 1988);
- At least three species of snappers, *Etelis coruscans*, *Etelis carbunculus*, and *Pristipomoides filamentosus*;
- Deep-sea precious corals, including pink (*Corallium secundum*, depth range 1,300 to 5,000 feet or 400-1,500 meters), gold (*Gerardia* sp., depth range 1,000 to 1,300 feet, or 300-400 meters), and bamboo (*Lepidisis clapa*, depth range 1,100 to 1,600 feet or 330-490 meters) corals (Western Pacific Regional Fishery Management Council 1979).

Observations made during biological investigations of the N\_wiliwili Disposal Site did not reveal any precious corals (see Table 4-1), and no commercially significant deep precious coral beds have been reported nearby. Even if some were to be present, because deep-sea benthic species are distributed at similar depths on the slopes of all the main Hawaiian Islands, only a very small proportion of the total habitat of any of these species could conceivably be found near the N\_wiliwili Disposal Site (Chave and Jones 1991).

Several general characteristics of the deep-sea benthos in the N\_wiliwili Disposal Site are relevant to predicting potential effects. First, deep-sea species typically are very broadly distributed, making it virtually certain that species occurring on the deep slope off Kaua'i are distributed throughout the main Hawaiian Islands. Second, the seafloor near the N\_wiliwili Disposal Site is a relatively high-energy environment by deep-sea standards; consequently, the benthos within the area is likely to be relatively well adapted to withstand water currents and mobile sediments. Because of low food availability and low temperatures in the deep ocean, deep-sea species typically have low metabolic rates (e.g., Gage and Tyler 1991). These low metabolic rates would be expected to allow deep-sea benthos to withstand CO<sub>2</sub> or oxygen stress for longer than species with higher metabolic demands. At the same time, deep-sea species also generally are characterized by low rates of growth, reproduction, and population recovery (Gage and Tyler 1991, Smith 1994). Thus, any effects resulting from the *Field Experiment* would tend to persist longer than effects in shallow-water settings.

No Federally listed endangered or threatened species (see Section 4.1.4) are known to occur at the deep seafloor near the experimental site or on the deep southeastern slope of the Island of Kaua'i.

#### 4.1.4.2 Midwater Marine Life (Depth range: 650 – 3,300 feet, ~200 – 1,000 meters)

Below about 650 feet (200 meters), plankton biomass declines almost exponentially with increasing depth down to about 6,600 feet (2,000 meters) (Barnes and Hughes 1999). Organisms in this relatively poorly studied region depend on the mixed surface waters above for virtually all of their food. Some organisms in the upper half of this layer migrate to surface waters to feed at night; others feed on migratory animals or on organic material that sinks from surface waters.

In these very clear waters, sufficient light exists for very low levels of photosynthesis down to perhaps 1,100 feet (350 meters), though very little photosynthesis occurs below 500 feet (150 meters) and the effectiveness of color vision disappears below about 1,300 to 1,500 feet (400-450 meters). Below 1,500 feet (450 meters) animals see only a faint glimmer of light from above, and bioluminescence becomes common. Virtually no sunlight penetrates beneath this zone. Other environmental gradients in this zone include: (i) a decrease of temperature from about 80° F (27° C) at the surface in summer to about 40° F (5° C) at the bottom, (ii) an oxygen minimum zone between 2,000 and 2,300 feet (600 and 700 meters), and (iii) an increase in hydrostatic pressure of about 15 pounds per square inch (1 atmosphere) every 33 feet (10 meters).

**Table 4-1. Observations of Benthic Fauna at the N\_wiliwili Disposal Site**

General Category	Species or Group	Comments
Foraminifera		
	<i>Cibicides lobatulus</i>	
	<i>Bolivina glutinata</i>	
	<i>Cassidulina sp.</i>	
Micromollusks		
	<i>Scissurella sp.</i>	Most abundant micromollusk
	<i>Benthonella spp.</i>	
	<i>Cephalaspids</i>	Rare
	<i>Bivalves</i>	Rare
Polychaetes		
	<i>Ditrupa arietina</i>	Most abundant polychaete
	<i>Serpulid sp.</i>	Tube fragments
	<i>Polynoid sp.</i>	
	<i>Nereid sp.</i>	
	<i>Goniada brunnea</i>	
	<i>Vermiliopsis sp.</i>	
	<i>Filograna implexa</i>	
Bryozoa (most commonly observed groups only)		
	<i>Entalophora sp.</i>	
	<i>Tubulipora atlantica</i>	
	<i>Tubulipora flexuosa</i>	
	<i>Crisina radians</i>	
	<i>Diaperoecia major</i>	
	<i>Schizoporella decorata</i>	
	<i>Parasmittina sp.</i>	
	<i>Rhynchozoon sp.</i>	
	Family Celleporidae	
	Aschophora, unk. Sp.	
Other Invertebrates		
	Sponges	
	<i>Spatongoidea spp.</i>	
	<i>Ebalia sp.</i>	

Source: COE 1977a, COE 1977b

Densities of vertebrates are very low at these depths, though some species of large, surface-associated fishes, marine mammals, and sea turtles may occasionally forage this deep. The most ubiquitous and visible organisms are the mesopelagic micronekton, which are composed primarily of small fishes, shrimps, and squids.

Reid *et al.* (1991) describe a ‘mesopelagic-boundary community’ found in Hawaiian waters at bottom depths of approximately 1,300 to 4,000 feet (400 to 1,200 meters). This community is composed of fourteen species of fishes (Argentinidae, Astronesthidae, Neoscopelidae, one species each; Sternoptychidae, four species; Myctophidae, seven species), five shrimps (*Gnathophausia longispina*, *Janicella spinicauda*, *Opophorus gracilirostris*, *Pasiphaea truncata*, *Sergia fulgens*), and four squids (*Chroteuthis imperator*, *Abralia astosticta*, *Abralia trigonura*, *Iridoteuthis iris*). The mean biomass of the mesopelagic-boundary community sampled off O‘ahu was strongly dominated by shrimps (Reid *et al.* 1991). As the name implies, the offshore edge of this community marks the transition

between Hawaiian and open-ocean midwater communities. The size of this midwater habitat greatly exceeds that of any other habitat in all of the Hawaiian Islands.

Federally listed endangered or threatened species that may occasionally occur in waters of this depth include Green (*Chelonia mydas agassizii*), Pacific Hawksbill (*Eretmochelys imbricata bissa*), Olive Ridley (*Lepidochelys olivacea*), Loggerhead (*Caretta caretta*), and Leatherback (*Dermochelys coriacea schlegelii*) sea turtles, as well as the Hawaiian Monk Seal (*Monachus schauinslandi*). Humpback whales (*Megaptera novaeangliae*) winter in Hawaiian waters; Finback (*Balaenoptera physalus*), Blue (*Balaenoptera musculus*), Right (*Eubalaena glacialis*), and Sperm (*Physeter macrocephalus*) whales are rarely sighted or detected by hydrophones in Hawaiian waters (Tomich 1986).

#### 4.1.4.3 Surface Ocean Marine Life (depth: 0 – 650 feet, 0-200 meters)

The most abundant and the only ubiquitous organisms of the surface waters are planktonic organisms including, most prominently, bacteria, algae (phytoplankton), protozoans, and zooplankton (Karl 1999). Common zooplankton types in coastal Hawaiian waters include copepods, chaetognaths, appendicularians, shrimps, amphipods, pteropods, and a variety of other invertebrates, as well as larval fishes. Many of these organisms migrate to waters below the thermocline during the day. The clear blue offshore waters in Hawai'i result from the very low densities of phytoplankton that are found in the oligotrophic waters of the North Pacific central gyre. Important phytoplankton taxa include prochlorophytes, coccolithophorids, flagellates, dinoflagellates, and diatoms.

A considerable diversity of fish are likely to exist in the nearshore waters around N\_wiliwili Harbor, but the vast majority of these are directly associated with the shallow seabed. The surface waters above the N\_wiliwili Disposal Site are the habitat of numerous pelagic fishes in a number of families, including tunas, jacks, billfishes, swordfishes, and dolphin fishes. Pelagic fishes are generally highly mobile and, while they may occur in large schools, they have overall very low average densities.

As previously mentioned, several threatened and endangered marine species can occur in the open ocean near the Hawaiian Islands. The Humpback whale occurs routinely in the waters around the main Hawaiian Islands during the winter months (Marine Sciences Group 1986). However, the Hawaiian Islands Humpback Whale National Marine Sanctuary does not include any waters near the N\_wiliwili Disposal Site. Blue, Right, Finback, and Sperm whales also occur rarely in Hawaiian waters (Tomich 1986). The monk seal is endemic to Hawai'i, but is most common in the northwest Hawaiian Islands and most frequently occurs in coastal waters.

The five species of sea turtles mentioned above (all endangered or threatened) have been reported in Hawaiian waters, but there are no known breeding or nesting areas for these turtles near the N\_wiliwili Disposal Site. Sea turtles are commonly sighted in the nearshore waters off Kaua'i.

## 4.2 WATER QUALITY EFFECTS

The release of liquid carbon dioxide (CO<sub>2</sub>) during the *Field Experiment* would produce a temporary and localized effect on water quality. The anticipated behavior of the carbon-rich plume and the resultant water quality changes are described below.

### 4.2.1 EXPERIMENT-PHASE EFFECTS ON MARINE WATER QUALITY

Mathematical models, laboratory tests, and oceanographic measurements were used to evaluate the effect that the proposed *Field Experiment* could have on the environment. They indicate that its principal effect would be the creation of a cloud of liquid CO<sub>2</sub> droplets and the subsequent dispersal of CO<sub>2</sub>-enriched seawater. Because of the importance that physical processes affecting the dissolution of CO<sub>2</sub> into the world's oceans have for understanding global warming, they have been the subject of intense scientific study by several research groups, each of which has developed its own approach to modeling these complex processes. The evaluation of potential impacts presented in this

report is based on the computer model of B. X. Chen of the Tsukuba Division of the Japanese Research Institute of Innovative Technology for the Earth (RITE). This model is fully three-dimensional, includes consideration of the dynamic and chemical behavior of both the pure liquid CO<sub>2</sub> phase (transport and dissolution of the droplets) and the receiving seawater, and has benefited from more than two years of development (Chen et al. 2001). The model has been compared with other researcher's work on this problem and gives very similar results. The current status of development of these models is presented in Appendix D.

The simulations predict that a near-field steady state will be established after about 20 to 30 minutes of discharge, with all of the liquid CO<sub>2</sub> being dissolved within this time after discharge. Because of this, and to limit the use of costly computer facilities, Dr. Chen simulated the discharge for a period of one hour. To simulate discharges longer than one hour for this environmental assessment, we simply expand the plume in the down-current direction, accounting for the current speed and the period of discharge.<sup>8</sup>

The computer simulations use a discharge rate for CO<sub>2</sub> of 9.5 gallons per minute (0.6 kilogram per second, the maximum that would be used during the experiment), an initial droplet diameter of 0.31 inches (8 millimeters), and two different seafloor ocean current profiles. The model calculates the size distributions of the CO<sub>2</sub> droplets in the near field as well as pH distribution in the near- and far-field.<sup>9</sup>

The behavior of the CO<sub>2</sub> was modeled at two different current speeds. The base case profile (lower axis in Figure 4-5) is based on actual measurements of currents at deep-water sites near the Hawaiian Islands. The fast-current profile (upper axis in this figure) is the identical shape, but the assumed current speed is three times as fast. This "fast-current" profile includes current speeds that are higher than speeds that would be acceptable for the safe and meaningful conduct of the *Field Experiment*; they are also higher than any current speeds documented at these deep-water sites for more than a few tens of minutes at a time. Thus, taken together, these two simulations are believed to bracket the anticipated current conditions that would be encountered at the N\_wiliwili site, with the upper bound of the current speed being clearly higher than the fastest that would actually be experienced.

The results of these computer simulations are summarized in Figure 4-6, Figure 4-7, Figure 4-8, and Figure 4-9. Figure 4-6 presents a vertical section through the center of the slow-current discharge plume, showing the predicted distribution of pH and CO<sub>2</sub> droplet size immediately after the maximum discharge period of two hours is completed. Figure 4-7 shows the same vertical sections simulated using the hypothetical fast-current profile.

Figure 4-8 shows horizontal sections of the pH distribution for both the slow and fast current regimes. These sections were selected at 79 (24.1 m) and 47 (12.4 m) feet above the seafloor, where the minimum values of pH are predicted by the model for the low-current and high current simulations, respectively. The horizontal sections are depicted both with a uniform scale (which best illustrates the relative lengths and widths of the predicted plumes), and also at exaggerated scales (which permits clearer depiction of the distributions of pH within the plumes).

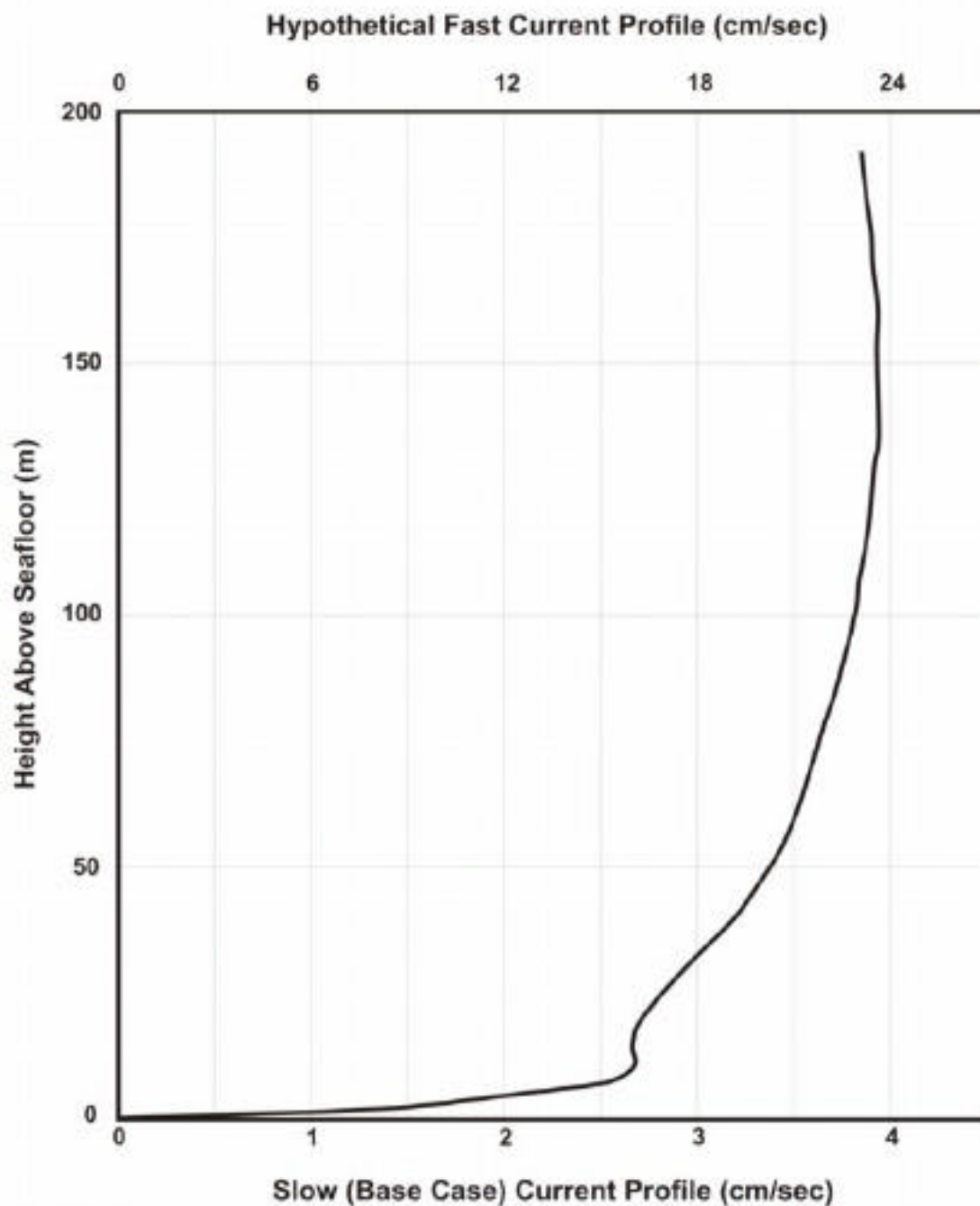
Figure 4-9 places these two-hour plumes within the context of the N\_wiliwili Disposal Site. This figure assumes, consistent with data collected at other N\_wiliwili and other Hawaiian sites, that the seafloor currents will be directed parallel to the bathymetric contours of the island.

Liquid CO<sub>2</sub> injected by the *Field Experiment* would exist in three different forms: (i) droplets of liquid CO<sub>2</sub> with density lower than seawater; (ii) thin coatings of solid mixtures of CO<sub>2</sub> and water

<sup>8</sup> This simplification produces a pH plume that has a relatively larger core of more acidic water close to the discharge point than would exist in reality. This is because the near-field, which has reached a steady state, is also expanded. It also produces a plume that is slightly less dispersed than would be expected in the actual situation, because the additional turbulent dispersion that would occur after one hour is not included.

<sup>9</sup> For a definition of "near-field" and "far-field," see Section 4.2.2.1.1 (footnote 3).





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Source:

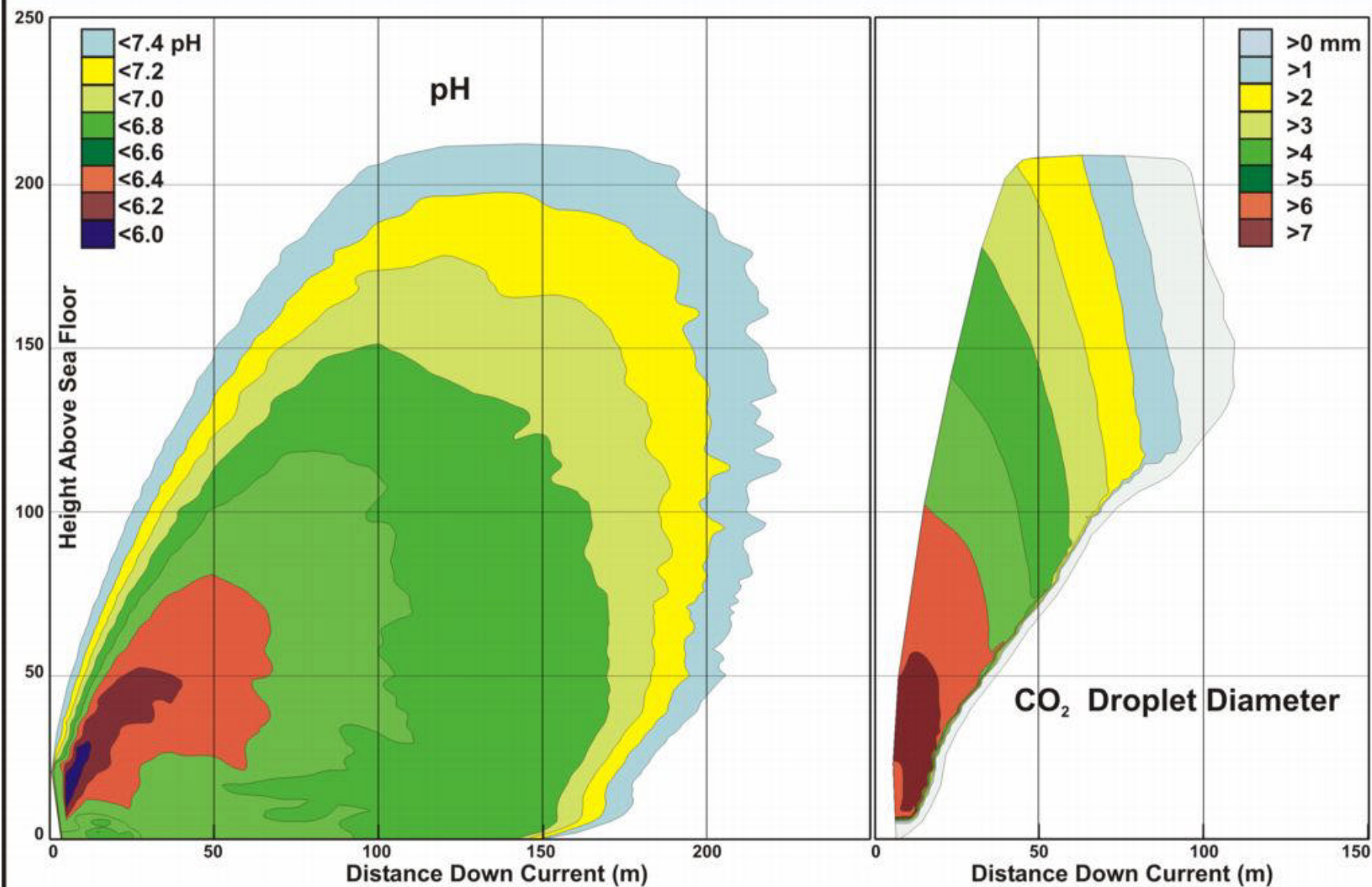
Research Institute for Innovative  
Technology for the Earth (RIIE)

Legend:

Figure 4-5:

**Current Profiles Used  
In Computer  
Simulation**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment



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Source: Chen et al. (2001)

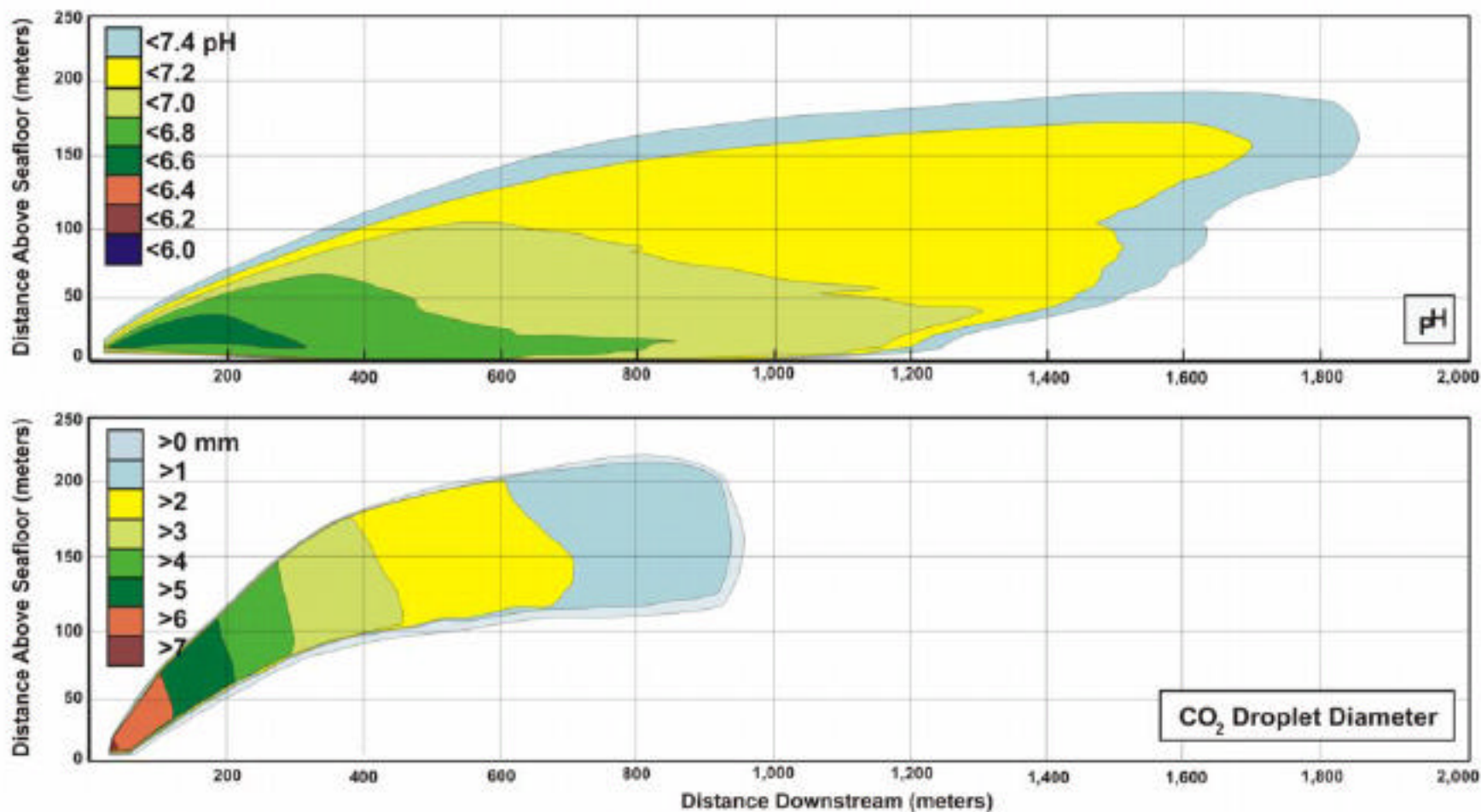
Legend:

Vertical Cross-section of plume after completion of 2-hour liquid CO<sub>2</sub> release. This represents the maximum extent achieved by the plume in a current of about 3 cm/sec. This is a commonly observed current speed at these water depths.

Figure 4-6:

**Centerline Vertical Section  
of Discharge Plume (Slow Current)**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment



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**Source:**

Chen (2001)

**Legend:**

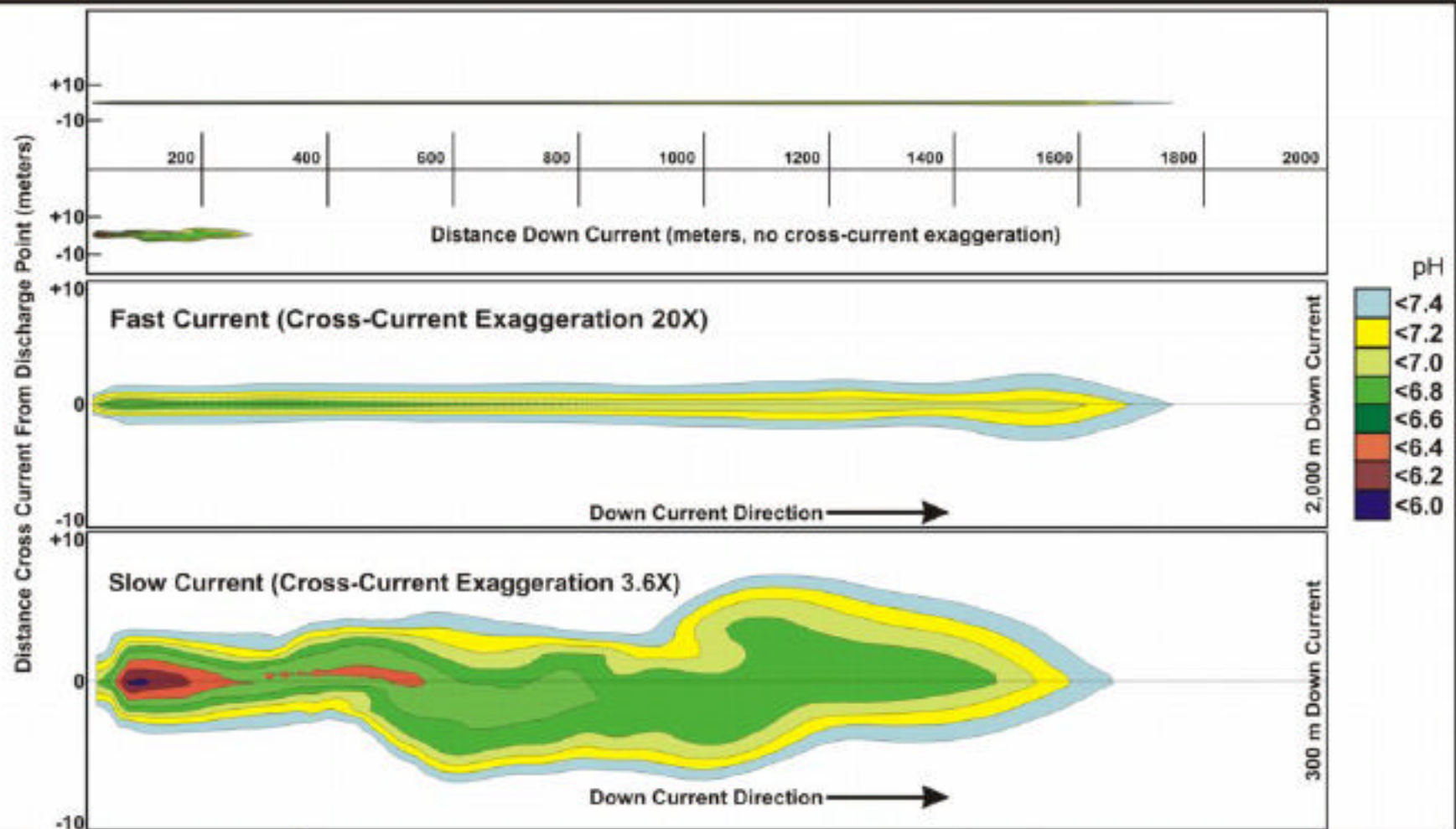
Vertical Cross-section of plume after completion of 2-hour liquid CO<sub>2</sub> release. This represents the maximum extent achieved by the plume under a hypothetical 24 cm/sec current. No current speeds of this magnitude have been observed to persist in Hawaiian waters at the planned water depth for more than a few tens of minutes.

**Figure 4-7:**

## Centerline Vertical Section of Discharge Plume (Fast Current)

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment





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Source:

Chen (2001)

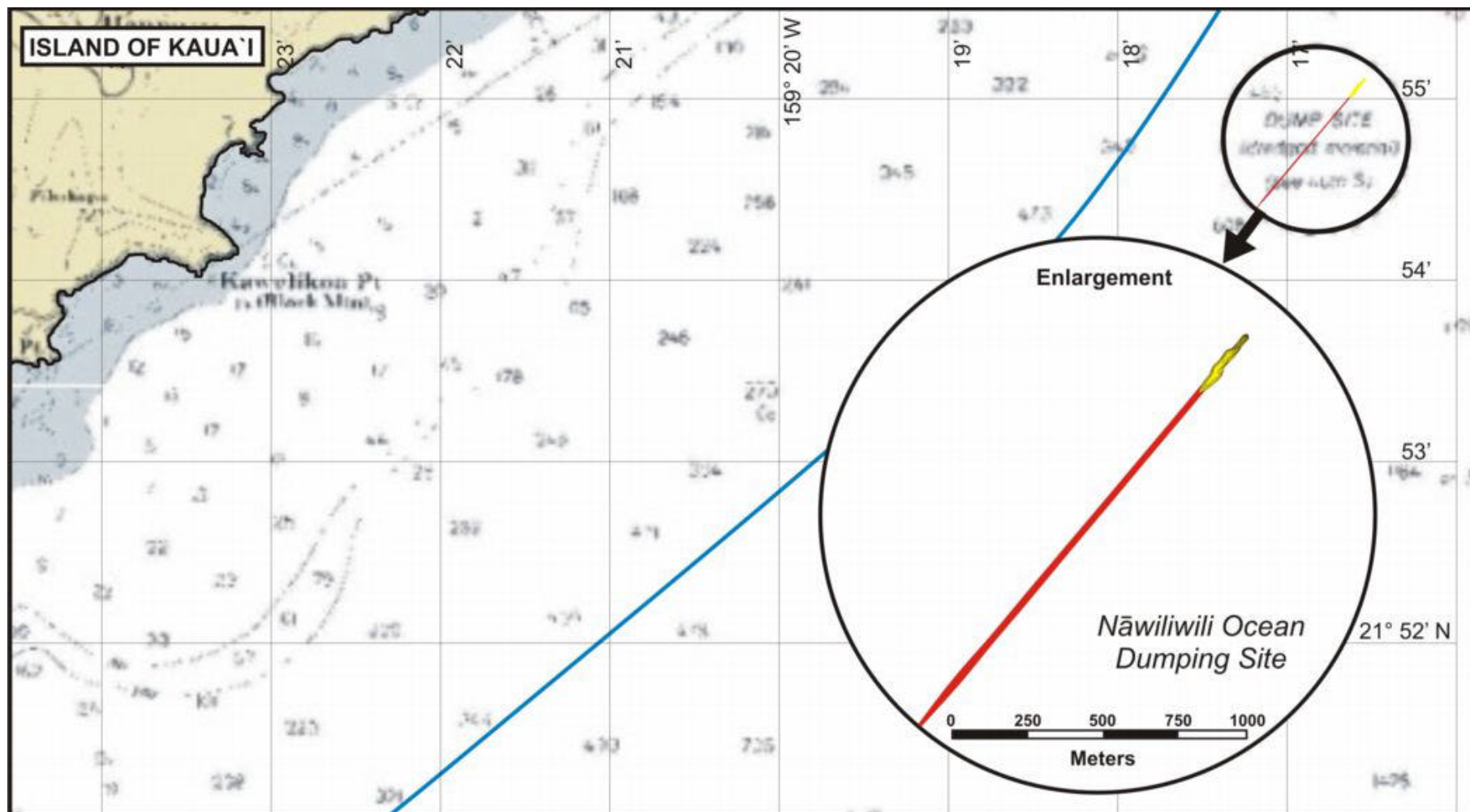
Legend:

Horizontal Cross-sections of plume after completion of 2-hour liquid CO<sub>2</sub> release. Fast Current represents the maximum extent achieved by the plume under a hypothetical 24 cm/sec current. No current speeds of this magnitude have been observed to persist in Hawaiian waters at the planned water depth for more than a few tens of minutes. Slow Current speed is about 3 cm/sec. This is a commonly observed current speed at these water depths.

Figure 4-8:

## Horizontal Sections Through Discharge Plumes

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment



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**Source:**

Chen (2001)  
NOAA Chart No. 19381

**Legend:**

-  Anticipated Maximum Plume Size  
(Low Current; pH<7.37) After  
2-hour CO<sub>2</sub> Release
-  Hypothetical Maximum Plume Size  
(High current speed) After 2-Hour Release
-  Three-Mile Limit  
of State Waters

0 1,000 2,000  
m



Figure 4-9:

## Hypothetical Plume Dispersion At Nāwiliwili Site

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

(termed hydrates or clathrates) that form on the surface of CO<sub>2</sub> droplets; and (iii) CO<sub>2</sub> dissolved in seawater. The physical and chemical effects predicted by modeling each of these forms of CO<sub>2</sub> are discussed separately below.

#### 4.2.1.1 Droplet Phase of the Plume

When liquid CO<sub>2</sub> discharges under pressure through a nozzle, distinct droplets (similar to those from a water sprinkler) are created. Because these droplets are slightly less dense than the surrounding seawater, the CO<sub>2</sub> droplets produced by the *Field Experiment* would rise from the discharge nozzle; thus, they would not affect the deep seafloor. Subsequent processes would dissolve and disperse the droplets, preventing them from reaching surface waters. The released carbon dioxide would be at essentially the same temperature as the ambient water. Consequently, no detectable cooling of the seawater surrounding the discharge platform would be expected.

The graph on the right side of Figure 4-6 shows a vertical cross-section of the predicted behavior of the droplet cloud for the slow-current case. Here, the droplet cloud would be expected to persist for a distance of approximately 330 feet (100 meters) down-current and to be about 700 feet (210 meters) high. The bottom graph in Figure 4-7 shows the droplet plume for the fast-current case. Here the CO<sub>2</sub> cloud extends to a maximum height of about 700 feet (210 m) above the seafloor and to a maximum downstream length of about 3,000 feet (900 m). Though CO<sub>2</sub> is colorless, water clarity within the droplet cloud would be slightly reduced (CO<sub>2</sub> has a different refractive index than seawater, so the droplets would be visible). Discharge experiments that were carried out in a high-pressure vessel simulated the deep-water discharge (Masutani *et al.* 2000a, Masutani, *et al.* 2000b). Pictures of the droplet cloud generated in these experiments (Figure 4-10) provide an indication of the way the droplets in the *Field Experiment* would appear if there were sufficient light to see them.

#### 4.2.1.2 Formation of Hydrate Coating

Under the physical conditions expected at the *Field Experiment* site, complexes of water and carbon dioxide known as “hydrates” or “clathrates” would form at the CO<sub>2</sub> droplet surface. During the *Field Experiment*, the CO<sub>2</sub> would be released in such a way that droplets would remain buoyant even with a hydrate coating. Thus, these droplets are not expected to impact the seafloor.

#### 4.2.1.3 Dissolution

The droplets and hydrates are ultimately unstable and would dissolve in the deep seawater within a relatively short time after their release, on the order of 30 minutes. The key chemical reactions of this process would be as follows:

- a.  $\text{CO}_2(\text{droplets}) \rightarrow \text{CO}_{2(\text{aq})}$
- b.  $\text{CO}_{2(\text{aq})} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3$
- c.  $\text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^-$
- d.  $\text{HCO}_3^- \rightarrow \text{H}^+ + \text{CO}_3^{2-}$

As indicated by the equations, droplets would first dissolve into the water (a), react with water to form carbonic acid (b), rapidly dissociate partially both to bicarbonate and carbonate anions, and generate free acid, or protons (H<sup>+</sup>) (c and d). Although a dissolved droplet would not be visible to the naked eye, the water containing the carbon dioxide could be distinguished from the rest of the seawater principally by a lowered pH (e.g., Stumm and Morgan 1981). A threshold of pH = 6.5 was chosen as the level below which acute effects on biota could occur. This threshold was based on experimental and field studies of the relationships between pH and marine life (Section 4.3.1.2, below). These dissolution reactions would have no substantial effect on the levels of dissolved oxygen in the affected seawater (C.S. Wong, 2000, Personal Communication).



**5 mm Nozzle  
Fast Discharge**



**5 mm Nozzle  
Slow Discharge**



**2 mm Nozzle  
Fast Discharge**



**2 mm Nozzle  
Slow Discharge**

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Prepared By:



Source:  
Matsutani et al. (2000)

Figure 4-10:

**Laboratory Generation of  
Liquid CO<sub>2</sub> Droplets**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment



Surface seawater has a typical saturation value of 33 mmol/l for total dissolved inorganic carbon (Teng *et al.* 1996). This corresponds to a pH of 4.88. Saturation value increases, and the corresponding pH value at saturation decreases, with increasing water depth. Degassing can occur only when the saturation value has been exceeded. The computer models used here and other models developed for this program (see Appendix D) indicate that pH values well above 5 would be reached within 5 feet of the release point. For this and other reasons, a sudden release of CO<sub>2</sub> into the atmosphere, similar to the dramatic and tragic release from Lake Nyos (Cameroon, Africa) that occurred in 1986 (Holloway 2000), would not be possible in the *Field Experiment*.

#### 4.2.1.4 Advection, Dispersion, & Diffusion: The Spatial & Temporal Extent of the Plume

Deep-water currents would carry the CO<sub>2</sub>-enriched seawater away from the release point (a process termed advection). When all the CO<sub>2</sub> droplets have dissolved, the only measurable manifestation of the discharge would be the depression of pH caused by the dissolution reactions discussed above. Turbulent eddies would mix the affected water with surrounding seawater, dispersing the dissolved CO<sub>2</sub> (also sometimes called “turbulent diffusion”).

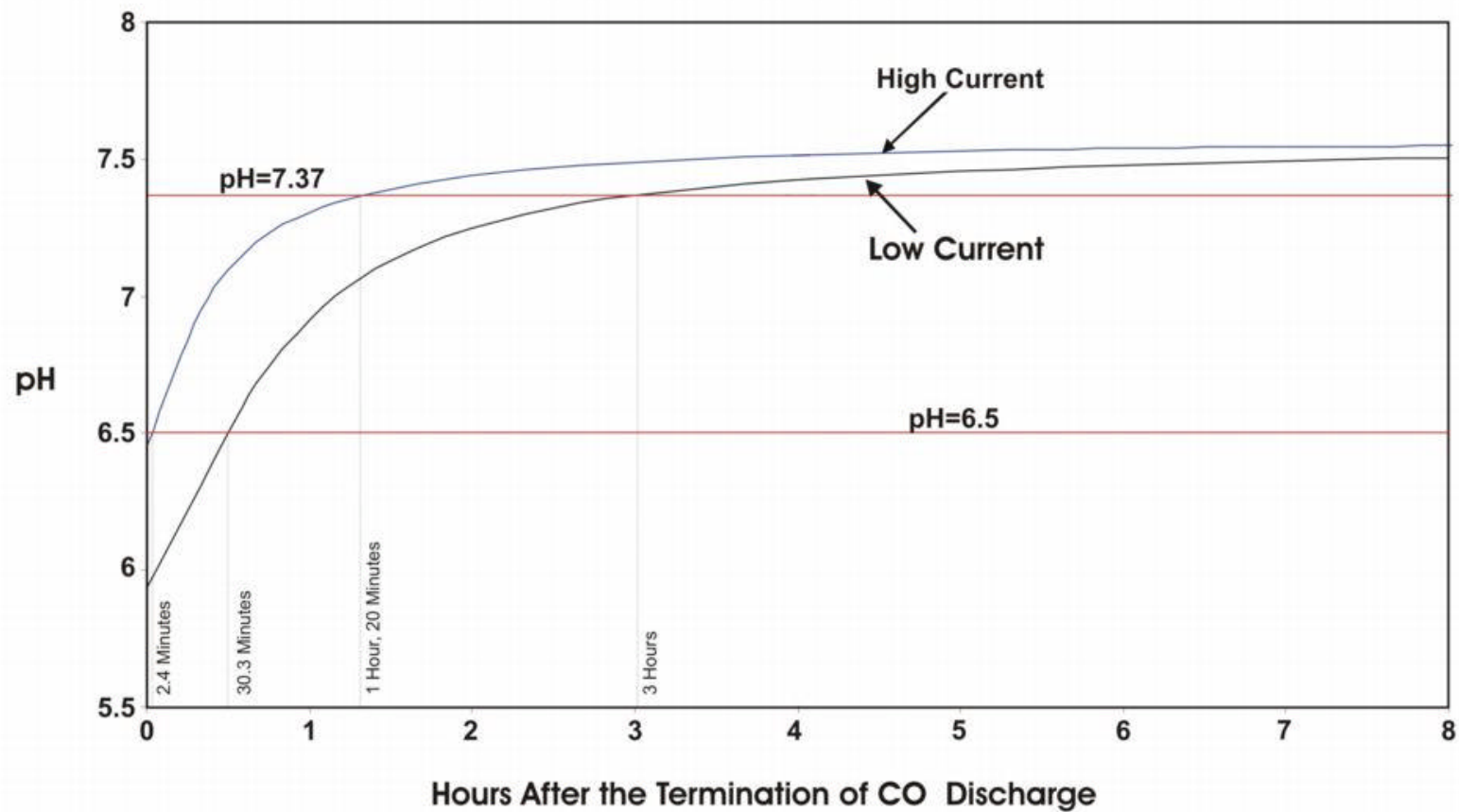
The graph on the left side of Figure 4-6 shows the predicted vertical distribution of pH in the slow-current simulation after two hours of discharge. The shape of the pH plume is similar in the vertical to that of the droplet cloud, with a maximum height of about 700 feet (210 m) above the seafloor, but it would have a down-current length of about 660 feet (200 m). The major difference between the droplet cloud distribution and the pH distribution is that the droplets form a relatively narrow rising plume that does not settle toward the seafloor, whereas the pH is altered through a broader column. The shape of the reduced-pH area is due to the gravity-driven settling of the CO<sub>2</sub>-rich seawater, which has a slightly higher density than the ambient seawater. As shown in the graph on the bottom of Figure 4-8, the width of this plume would be about 50 feet (15 m) at its widest extent. The top graph in Figure 4-7 and the middle graph in Figure 4-8 show the predicted maximum extent of depressed pH for the fast-current plume after a two-hour discharge. Its dimensions would be about 5,900 feet (1,800 m) long, 650 feet high (195 m), and a maximum of 16 feet wide (5 m).

By comparing the low-current and high-current simulations, it is clear that relatively higher volumes of more acidic water, e.g. below pH = 6.5, are generated under low-current conditions, whereas relatively higher volumes of water just below ambient pH values are generated under high-current conditions. In other words, high currents have the effect of smearing the plume through a larger volume than low current speeds, while also reducing the effect on the average pH value within the plume. Overall, the return of the environment to normal ambient conditions is accelerated by high currents.

The approximate volume of water subject to pH levels of 6.5 or lower would be at its greatest, on the order of 10,000 m<sup>3</sup> for the low-current simulation and less than 1,000 m<sup>3</sup> for the high-current simulation, after two hours (the maximum discharge time that would occur with the planned *Field Experiment*; see Appendix C). The maximum volume of water subject to pH levels lower than 7.37 (0.2 pH units below the ambient pH value, see Section 4.2.3 for a discussion of the significance of this differential) would be about 300,000 m<sup>3</sup> for the low-current simulation and 700,000 m<sup>3</sup> for the high-current simulation.

Figure 4-11 describes the subsequent evolution of the most acidic part of the plume, subjected to turbulent diffusion, after a discharge of two hours duration. As shown in this figure, the low-current simulation predicts that pH levels above 6.5 would be reached after about 30 minutes, while the simulation predicts that it would take less than three minutes in the high-current case to disperse to pH levels above 6.5. These calculations were repeated for all points along the down-current axis of the plume. Combining dispersion and current speed, it was shown that the maximum extent of the drifting plume, before it dissipates completely, is less than 500 m down-current for the slow-current case and about 2,100 m down-current for the fast-current case.





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Figure 4-11:

**Minimum Values for pH  
in the Plume Over Time**

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

It is worth noting that this figure makes it very clear why the researchers planning the *Field Experiment* would chose not to conduct the experiment at the exceedingly high current levels used in the high-current simulation. Simply put, the plume produced by releasing the CO<sub>2</sub> under such conditions would be too short-lived to permit reliable characterization through available field measurements.

#### 4.2.2 OTHER WATER QUALITY EFFECTS

Other activities carried out during the *Field Experiment* would include standard oceanographic investigations of the carbon dioxide plume's characteristics. These activities would include temporary deployment of instrument packages and one or two remotely operated vehicles (ROVs) or submersibles to measure key parameters. The U.S. National Oceanographic and Atmospheric Administration has determined that use of these instruments creates no potential for significant environmental effects, including effects on water quality (15 CFR 970.701a). Research vessels would be equipped with U.S. Coast Guard-approved marine sanitation devices (33 CFR 159) to preclude unauthorized discharges of sanitary wastes. Research vessels would comply with U.S. Coast Guard regulations (33 CFR 151) and other applicable Federal and State of Hawai'i laws and regulations for the management of bilge and ballast water to minimize pollution and the introduction of non-indigenous or exotic species into waters at the site of the experiment.

As discussed elsewhere in this report, the CO<sub>2</sub> droplets would cause a temporary, localized effect on water clarity within 100 to 200 feet of the release point. In addition, marker dyes, used to track the CO<sub>2</sub>-enriched seawater plume, would contribute a localized effect on water clarity near the release point. Two types of dye are under consideration for use during some of the releases, rhodamine-WT and disodium fluorescein (trade name uranine). For many years scientists and engineers have used both of these tracer dyes in freshwater and seawater systems to track parcels of water. Either dye would create a visible color in the seawater within at most 300 to 500 feet of the discharge point. Beyond this distance, the dye would be diluted to where it would be only detectable using specific sensors designed for that purpose. The absence of potential for toxic effects from these dyes is discussed in Sections 4.3.1.3 and 4.3.2.1.4. Because the effects on water clarity caused by the CO<sub>2</sub> droplet cloud and by the tracer dyes would both be localized and temporary, they would not have a substantial effect on seawater quality.

#### 4.2.3 RELATIONSHIP TO APPLICABLE WATER QUALITY STANDARDS

CO<sub>2</sub> itself is not a regulated pollutant and not subject to the National Water Quality Criteria that would be applicable at the N\_wiliwili Disposal Site. As discussed above, the only potential pollutant of concern for the *Field Experiment* is the acidity (depressed pH) that is produced as a consequence of the dissolution of the released liquid CO<sub>2</sub> into seawater. According to the EPA *National Recommended Water Quality Criteria For Non Priority Pollutants* (EPA 822-Z-99-001, April 1999, Footnote K) "For open ocean waters where the depth is substantially greater than the euphotic zone, the pH should not be changed more than 0.2 units from the naturally occurring variation or any case outside the range of 6.5 to 8.5." As discussed in Section 4.2.1, the pH reduction that would accompany the release of CO<sub>2</sub> would cause only localized, short-term excursions outside the normal range.

#### 4.2.4 ACCIDENT SCENARIOS (REASONABLE WORST CASE)

The flexible steel discharge tubing planned for use during the *Field Experiment* would be designed to withstand the stress of repeatedly lowering and raising the approximately 5-metric ton discharge platform, the internal pressure of the liquid CO<sub>2</sub>, and the external, hydrostatic pressure in the deep sea. The tubing would be designed to be coiled and uncoiled up to 150 times (JMC 2000. Personal Communication). Nonetheless, while unlikely, the possibility of a tubing failure cannot be completely discounted.

## AFFECTED ENVIRONMENT &amp; ENVIRONMENTAL CONSEQUENCES

If a failure were to occur, it would most likely happen at a point of greatest stress. In practice, this means the tubing would be most likely to fail either at the top or at the bottom; failure would also be most likely to occur while the platform is being raised or lowered or if the tubing were to become snagged on a protuberance from the seafloor.<sup>10</sup>

The important variables in evaluating the effect of a tubing failure would be the depth at which the break occurs and the amount of CO<sub>2</sub> that could potentially escape. While design of the tubing has not been finalized, the tubing would likely have an internal diameter of approximately 1.5 inches (3.81 centimeters). The volume of CO<sub>2</sub> contained within a 3,600-foot length of tubing with a 1.5-inch diameter would be 325 gallons (1.25 cubic meters).<sup>11</sup>

Failure Near the Surface. If the tubing would rupture at or near the surface (i.e., if the tubing develops a leak without being completely severed), the CO<sub>2</sub> would escape as a gas due to sudden depressurization. The rapid ascent of bubbles to the sea surface would probably prevent much CO<sub>2</sub> from entering the seawater. Hence, this scenario would have little potential to affect water quality. Once in the atmosphere, the CO<sub>2</sub> would rapidly disperse.

If completely severed at the surface, the tubing would fall to the seafloor. In reality, most of the liquid CO<sub>2</sub> in the tubing would vaporize, rise to the surface, and then vent into the atmosphere. Little CO<sub>2</sub> would dissolve into the water during this process. Once the broken end of the tubing sank below 1,500 feet (450 meters), hydrostatic pressure would be sufficient to keep any remaining CO<sub>2</sub> that escapes in a liquid state. The tubing would move erratically during the fall, thereby dispersing the CO<sub>2</sub> over a large volume of water. Because of these forces, the CO<sub>2</sub> released in the event of such an accident would have little effect on water quality.<sup>12</sup>

Failure Near the Bottom. If the tubing were to fail near the bottom, the most CO<sub>2</sub> that could be released would be the entire volume of CO<sub>2</sub> (325 gallons) in the tubing. In reality, the pressure inside and outside the break would quickly equalize and less would escape. Such a failure could release, over a relatively short period of time, about the same volume of CO<sub>2</sub> as would normally be released during 15-20 minutes of a planned test at the maximum discharge rate contemplated.

The impacts on water quality would depend upon many factors, including whether or not the broken tubing would remain attached to the platform and the extent to which hydrate formation around the break would restrict the rate of release. However, in any event, the water quality effect would only be a fraction of the modeled situation presented in Section 4.2.1. The probability of these failures is not known. Such an experiment has not been conducted, and yet the handling and transport of liquid CO<sub>2</sub> is commonplace worldwide. No specific statistics for failure of such marine transport and handling systems were available for this study.

#### 4.2.5 CLOSURE/TERMINATION-PHASE EFFECTS ON MARINE WATER QUALITY

The activities that would take place during the closure/termination phase of the *Field Experiment* would not affect water quality. The discharge platform, pipe, and monitoring instrumentation would be removed with no further activities anticipated at the site. These activities would have no measurable effect on water quality.

---

<sup>10</sup> Photographs of the seafloor taken by the studies conducted for the U.S. Corps of Engineers at the N\_wiliwili Disposal site (COE 1977b) revealed occasional patches of rocky outcrops, some appearing to rise 1 to 2 feet above the sediments. If the surface vessel that deployed the platform were to move substantially to either side of a designated location, the tubing could become stuck on a rock and, in effect, anchor the vessel. This could cause the tubing to break.

<sup>11</sup> The tubing length used, 3,600 feet, accounts for the 2,600 feet of vertical distance needed to reach the ocean floor plus the 1,000 feet of tubing that would lie on the ocean floor.

<sup>12</sup> Even if an assumption is made that all CO<sub>2</sub> in the tubing would dissolve in the surface layer with no subsequent release to the atmosphere, the maximum dimensions of the parcel of water that would experience a pH = 6.5 would be no more than 30 meters (100 feet) on a side. Even this parcel would be very short-lived; nowhere would pH remain below 6.5 for longer than 17 minutes, and the affected parcel could travel no further than 440 feet (133 meters) before being completely dissipated by turbulent mixing.

#### 4.2.6 WATER QUALITY EFFECTS OF NO ACTION ALTERNATIVE

If the *Field Experiment* was not conducted due to a No-Action decision by DOE, which would result in DOE's withdrawal from the international agreement under which the *Field Experiment* would be conducted, no changes in existing water quality would occur. If the *Field Experiment* was conducted without DOE participation, then the water quality effects would be similar to those presented for the N\_wiliwili Disposal Site.

### 4.3 EFFECT ON MARINE RESOURCES

The primary environmental effects of the *Field Experiment* would be on the deep-water marine resources near the *Field Experiment* site. Section 4.3.1 provides a general overview of the project elements that have potential to affect marine biological resources. Section 4.3.2 discusses the effects of conducting the *Field Experiment* at the N\_wiliwili Disposal Site. Section 4.3.3 describes the anticipated effects on marine biological resources under a No-Action decision by DOE.

The *Field Experiment* would not be expected to have a substantial adverse affect on the North Pacific Humpback whales (*Megaptera novaeangliae*). Additional discussion on Humpback whales is presented in Section 6.1.9. The absence of potential effects on sea turtles is discussed in Section 6.1.5.

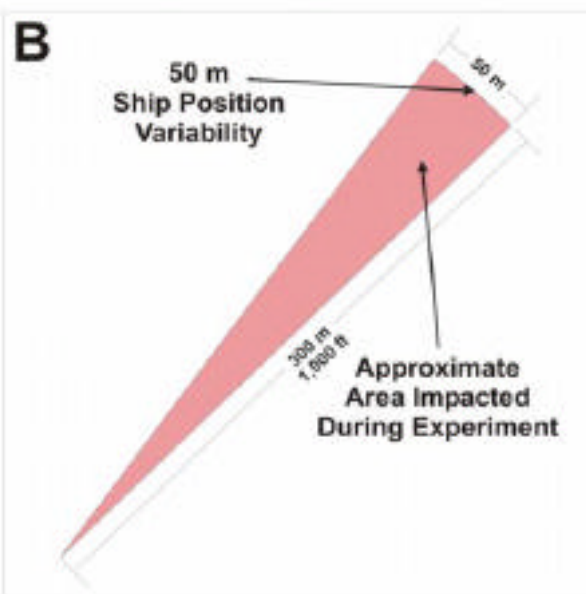
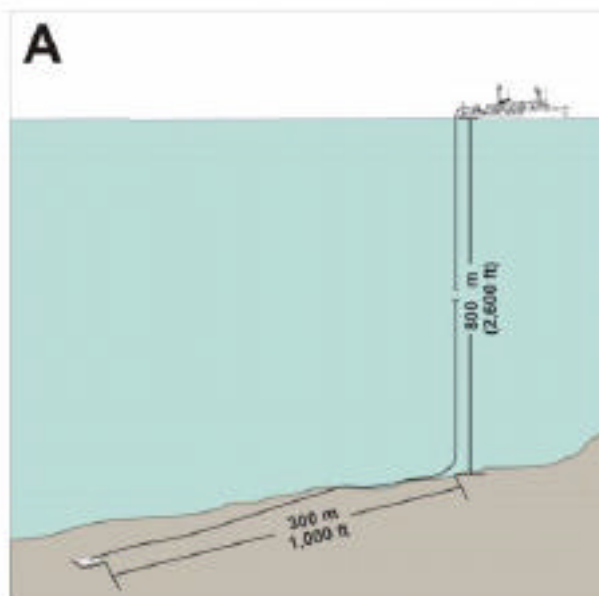
#### 4.3.1 PROJECT ELEMENTS WITH POTENTIAL TO AFFECT MARINE BIOTA

This subsection summarizes key aspects of the *Field Experiment* that have the potential to cause environmental effects. Section 4.3.1.1 describes the direct effects anticipated to result from emplacement of the discharge platform and tubing. Section 4.3.1.2 outlines the state of knowledge regarding the interaction between lowered pH levels in ocean water and marine life. Section 4.3.1.3 describes the characteristics of the oceanographic monitoring equipment that would be used for the *Field Experiment*, and Section 4.3.1.4 considers the scale of, and probable results from, accidental releases of CO<sub>2</sub> that could result from equipment failure or operational errors.

##### 4.3.1.1 Area Subject to Abrasion from the Discharge Platform and Tubing

The discharge platform (Figure 3-3), measuring about 7 by 13 feet (approximately 2 by 4 meters) and weighing 5 metric tons, could be lowered onto the seafloor as many as 10 times, though the current experimental plan calls for only two such deployments (see Appendix C). During each landing, the platform would likely leave an imprint in the seabed if it lands on soft substrate. The preliminary platform design incorporates a pointed leg at each corner. This configuration, which is intended to help affix the platform to the steeply sloping seafloor, would minimize the area over which the platform would contact the bottom. If all four legs would land on bare substrate each time the platform would be deployed, the contact area for 10 deployments would be minimal, probably no more than 40 square feet (4 square meters). Even if the platform unexpectedly landed on soft bottom during each of the 10 deployments so that the entire bottom rested on the seafloor, the contact area would be no more than 860 square feet (80 square meters), which would be too small to have a substantial deleterious effect on the benthos.

The tubing laid on the seafloor during each deployment of the platform would affect a larger area. Figure 3-1 shows the general methods that would be used for deployment of the tubing and discharge platform. Figure 4-12 illustrates the worst-case estimate of the area that would be impacted. Tubing could extend approximately 1,000 feet (300 meters) away (as measured horizontally) from the platform. This horizontal displacement would keep the vertical segment of the tubing (i.e., the part that extends through the water column from the surface vessel to the seafloor) well clear of the space in which the ROVs and submersibles would operate. Figure 4-12a shows the situation after complete deployment of the platform.



Prepared For:  
Pacific International Center  
for High Technology  
Research (PICHT)

Source:



Prepared By:  
Planning Solutions, Inc. (2001)

Figure 4-12:

## Benthic Impact Area Estimate

Ocean Sequestration of  
CO<sub>2</sub> Field Experiment

While the vessel used for the deployment would have very good position-keeping capability, the vessel would not remain perfectly motionless for the entire duration of each deployment. The experimental design specifies that the vessel would remain within 80 feet (25 meters) of a desired position. Combined with the length of tubing that would rest on the seafloor, this position-keeping capability would define the maximum sector across which the tubing could sweep. This sector (with the platform as its center and the length of tubing on the seafloor as its radius) is sketched in Figure 4-12b. A seabed area of about 1.84 acres could be impacted.

However, the vessel and platform would probably not be in precisely the same location each time the platform would be deployed (although they are likely to be close). Thus, the tubing could affect a different part of the seafloor during each deployment of the platform. Assuming that absolutely no overlap would exist between successive deployments of the platform and tubing (a highly unlikely assumption) and that a maximum of 10 deployments would be made, then loose rocks could be displaced and mounded sediments could be disturbed over a maximum seafloor area of 18 acres. In reality, the actual effect is far more likely to be toward the lower end of this range than toward its upper end.

#### 4.3.1.2 Mechanism Through Which Lowered pH Could Affect Marine Life

Injection of very large amounts of anthropogenic CO<sub>2</sub> into seawater over a long period could affect the rate of deposition or loss of calcium carbonate by organisms. The *Field Experiment* would involve far too small a release and far too short a time to cause such chronic effects. Organisms that live at the depth where the *Field Experiment* would be conducted are accustomed to an environment where calcium carbonate is stable. The temporary depression of pH caused by the *Field Experiment* CO<sub>2</sub> release would briefly produce chemical instability, but the relatively slow process of carbonate dissolution would not be substantially affected.

The kind of short-term CO<sub>2</sub> release planned for the *Field Experiment* would theoretically be capable of affecting development, reproduction, and survival of marine organisms through physiological effects of acidosis. The potential for such acute effects is discussed below. Studies of the effects of increased CO<sub>2</sub> levels on marine organisms have only been recently initiated and few data are available. Most prior research into the effects of depressed pH on marine organisms has concentrated on the effects of acid discharge from industrial outfalls and the release of acidic wastes from barges. Auerbach *et al.* (1997) reviewed available laboratory studies on the effects that time exposures to lowered pH can have on different sorts of marine life. Figure 4-13 presents a summary of these laboratory studies. This figure also shows the predicted time exposure to depressed pH of the most acidic part of the *Field Experiment* release. This figure clearly illustrates that the proposed *Field Experiment* would not produce the conditions determined from these laboratory studies to cause mortality in marine life.

Perhaps the best available natural analog to a release of anthropogenic CO<sub>2</sub> in the deep sea are the plumes of hydrothermal fluid emanating from vents on the Hawaiian seamount L\_‘ihi, located about 20 nautical miles southeast of the Island of Hawai‘i. The fluids venting from L\_‘ihi contain CO<sub>2</sub> concentrations as high as 18 parts per thousand (by weight) at a depth of about 3,300 feet (~1000 m; Karl *et al.*, 1988; Sedwick *et al.*, 1992).

Over a period of two weeks in 1997, injection of CO<sub>2</sub> into the deep-sea water near Hawai‘i by Pele’s Vents (located on L\_‘ihi) was on the order of 340 to 5,500 short tons (McMurtry 1998). This mass is 17 to 275 times the amount that would be injected over the course of the *Field Experiment*. There are no known reports of substantial adverse effects on marine organisms in the water column as a consequence of the L\_‘ihi vents, where animals passing through the vent field in the water column above the vents would not be adapted to the high CO<sub>2</sub> levels, and where the pH would be as low as the pH likely to be experienced in the *Field Experiment*. Moreover, this is true even though the release from the L\_‘ihi vents occurs over very long periods of time and is accompanied by other factors that are even more inimical to biological activity.

The existence of naturally occurring releases of large amounts of dissolved carbon in deep hydrothermal vents of volcanic origin on L\_‘ihi may prove very useful in future evaluations of the potential chronic environmental effects of ocean sequestration of CO<sub>2</sub>. However, the lack of a pure phase (liquid CO<sub>2</sub>) at release points on L\_‘ihi would eliminate strong buoyancy effects, the role of hydrate formation, the influence of dissolution kinetics, and other processes that are the objects of study for the *Field Experiment*. Also, there would be a lack of necessary experimental control, because the venting occurs sporadically at variable flow rates and at multiple sites.

A critical assumption of this analysis is the pH at (and below) which marine metazoans would begin to die after a brief exposure. Information on this subject is limited. In a study of the effects of CO<sub>2</sub> concentration on two echinoid and one gastropod species, Shirayama *et al.* (1999) reported very low mortality relative to controls at pH levels ranging from approximately 6.5 to 7.8. Significantly, no experimental organisms died during the first week of exposure to any of the reduced pH levels in this range (i.e., to an exposure period that would be much longer than any produced by the *Field Experiment*).<sup>13</sup>

In a study of the effect of pH on eggs, larvae, juveniles, and adults of flounder (*Paralichthys olivaceus*), Kita *et al.* (1999) reported that the younger life stages were the most sensitive. Approximately 40% of flounder larvae were found to survive exposure to 6.5-pH seawater for 6 hours, and about 20% survived exposure to 6.5-pH seawater for 24 hours. Auerbach *et al.* (1997) used literature data to report on the effect of pH and exposure time on a variety of holo- and meroplanktonic organisms; no mortality was predicted for those organisms after a 24-hour exposure to seawater with pH as low as 5.7. Mortality did not occur in the copepod *Temora longicornis* after 24-hour exposure to acidified seawater until the pH was reduced below 6.0 (Grice *et al.* 1973).

Taken as a whole, the data suggest exposure to seawater with a pH as low as 6.5 for periods of time less than 24 hours would not result in substantial levels of mortality for marine macrofauna and plankton. The data do suggest that water with pH levels below 6.5 would have some potential to harm certain marine organisms if they are exposed for a sufficient period of time. The limited studies also suggest that exposures to the greatest pH depression that would be produced by the fastest discharge rate over the time that a CO<sub>2</sub> plume would persist (a few hours) could harm (including kill) some marine organisms, but that this potential is limited to organisms approaching within a few feet of the release point. Unfortunately, insufficient data exist to establish precise dose-response relationships.

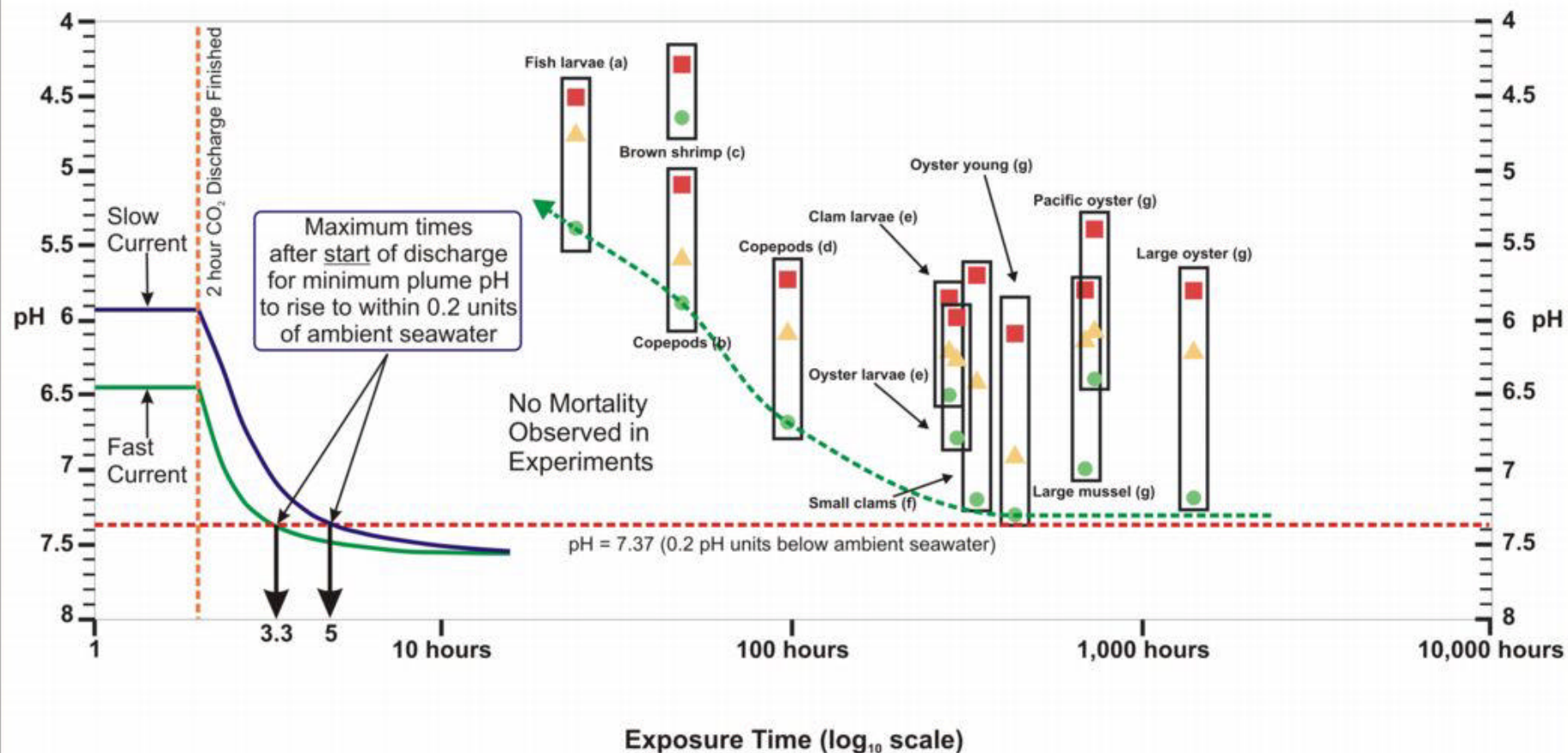
#### 4.3.1.3 Experimental Monitoring Devices

The other activities carried out during the *Field Experiment* would include standard oceanographic investigations of the discharge plume characteristics. These activities would include deployment of seafloor-moored instrument packages, ROVs, and submersibles to measure the key parameters of the discharge. The U.S. National Oceanographic and Atmospheric Administration has, through many years of conducting and observing such activities, determined that they have no potential for significant environmental effects (15 CFR 970.701a).

The tracer dyes planned for use in the *Field Experiment* are non-toxic at the concentration levels anticipated (<5 mg/l at a distance of 3 feet from the release point). Extensive testing of the dyes using a variety of aquatic organisms showed no toxic effects at concentrations below 10 mg/l (Keystone Corporation 2000).

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<sup>13</sup> The report notes that, at the highest acidity concentrations, the echinoderms appeared to be paralyzed for some time prior to death (after about 2 weeks). The report does not state either the length of time between initial exposure to decreased pH and the onset of paralysis or the response that might result if conditions returned to normal in less than two weeks.



**PREPARED FOR:**

Pacific Institute for High Technology Research (PICHTR)

**PREPARED BY:**



**SOURCES:** Auerbach et al. 1997  
Chen et al. 2001

**LEGEND:**

- Minimum pH for slow current simulation
- Minimum pH for fast current simulation
- - - Observed Limit for Mortality due to pH Exposure

**Marine Studies**

- (a) Brownell, 1980
- (b) Grice and Wiebe, 1971
- (c) Porumann, 1970
- (d) Rose and Williams, 1977
- (e) Calabrese and Davis, 1966
- (f) Bamber, 1987
- (g) Bamber, 1990



Figure 4-13:

## Biological Mortality Due to pH Exposure

Ocean Sequestration of CO<sub>2</sub> Field Experiment



#### 4.3.1.4 Mechanism Through Which Accidental Releases Could Affect Marine Life

As discussed above in Section 4.2.4, accidental releases of CO<sub>2</sub>, either on the sea surface or at the seafloor, would be of very short duration and cause only minor perturbations on surface or deep seawater. Accidental releases would not be expected to cause adverse impacts.

### 4.3.2 EFFECTS AT THE N\_WILIWILI DISPOSAL SITE

#### 4.3.2.1 Anticipated Seafloor Effects

The planned *Field Experiment* could potentially affect deep seafloor communities through (i) direct CO<sub>2</sub> effects, (ii) disturbance from repeated platform emplacement, (iii) seafloor scour by the CO<sub>2</sub> delivery tubing, and (iv) other miscellaneous effects. All of these effects would be localized.

##### 4.3.2.1.1 Direct CO<sub>2</sub> Effects on the Seafloor

As discussed in Section 0, small patches of seafloor near the platform could be subjected to pH levels below 6.5. Some mortality of benthic organisms dwelling within these patches would be likely, but they would be very difficult to detect due to the low densities and the high spatial variability characteristic of deep-sea sediment assemblages (Gage and Tyler 1991). Mortality on similar spatial scales frequently occurs naturally in deep-sea communities due to mounding and digging activities of seafloor animals (Kukert and Smith 1992). A potential for a seafloor impact from the *Field Experiment* would be created from the formation of plumes of CO<sub>2</sub>-enriched seawater with pH  $\leq$  6.5. Conservative plume-dispersion calculations previously outlined in Section 0 indicate that the plume from a test at the highest planned release rate would not contact the seafloor. However, if some unusual short-term turbulence were to occur, it is possible that a small area of seafloor could be affected.

The evidence presented in Section 4.3.1.2 from Auerbach *et al.* (1997) indicates that this exposure could stress some organisms but would be unlikely to be lethal. Shirayama *et al.* (1999), have reported toxicity to megafaunal organisms from exposures of a few hours, but do not address the shorter exposure period that might result from the proposed experiment. Marine biologists recognize that they have imperfect knowledge of the precise pH dose-response characteristics of the organisms that populate the seafloor at the depth of the planned *Field Experiment*. Moreover, the deep-sea communities that could be affected are characterized by very low rates of recolonization because of the low food availability at the deep seafloor (Smith and Hessler 1987, Kukert and Smith 1992). Together, these two considerations justify the caution that the project team is using in its approach to the *Field Experiment*.

When all factors are considered, the CO<sub>2</sub> released during the *Field Experiment* would not be likely to have a substantial effect on benthic fauna. However, in view of the uncertainty inherent in any research endeavor, one or more of the following actions could be implemented if needed to provide additional protection against unanticipated adverse effects:

- Monitor the actual behavior of the plume of seawater having a reduced pH if any substantial plume characteristics that were not predicted by preliminary modeling studies should be identified;
- Monitor acute effects on animals near the CO<sub>2</sub> release point during the course of the experiment;
- Include in the experimental protocol provisions to modify the release (with respect to rate, timing, current speed, location, or other factors) in response to any unanticipated adverse effects.

The feasibility and specific methods of implementing these actions are being developed by the project team. The draft experimental plan describing these protocols and monitoring activities is presented in Appendix C.

One aspect of the work undertaken to monitor benthic ecosystem response to the *Field Experiment* discharge is a component of the existing *Field Experiment* scientific program. Coffin, *et al.* (1999) are developing the means to determine how the basic metabolic processes in ambient bacterial populations at the site would be affected by the CO<sub>2</sub> discharge. The work would include measuring ratios and abundances of naturally occurring carbon isotopes<sup>14</sup> (<sup>13</sup>C and <sup>14</sup>C) in bacteria at the site before and after the *Field Experiment*, as well as laboratory culturing of the bacteria and measurement of how their growth rates vary with changes in pH. The object of these experiments would be to obtain information about how this very basic level of the ecosystem would be affected.

#### **4.3.2.1.2 Seafloor Effects of Repeated Platform Emplacement**

As discussed in Section 4.3.1.1, the total area that could be physically impacted by 10 deployments of the discharge platform would range from 5 square yards (4 square meters) to 100 square yards (80 square meters). Complete recovery of the disturbed patches to background levels of faunal abundance and diversity could take a number of years. However, disturbance on this scale would not cause any long-lasting negative impacts to any of the seafloor fauna at the population or species level.

#### **4.3.2.1.3 Seafloor Scour by the Injection Tubing**

As discussed in Section 4.3.1.1, an area of about 18 acres (8 hectares) of seafloor could be impacted by the maximum number of possible deployments of the platform and tubing. Movement of the tubing on the seafloor would adversely affect animals living on hard substrates. Video taken near the study site revealed few, if any, organisms attached to the rocks. Organisms that might be expected to occur on such substrates include non-hermatypic corals, sponges, and ascidians. Such organisms could be completely or partially destroyed by the movement of the tubing, or they could receive partial or complete protection from irregularities in the rock surface. Organisms with temporary or no attachments such as crinoids, echinoids, ophiuroids, holothurians, and decapods could be damaged, killed, or simply dislodged by the movement of the tubing.

Movement of the tubing could also affect animals living on or in soft sediments. Macrofauna could be damaged, killed, or simply dislodged by the movement of the tubing. Some infauna (predominantly small polychaete worms, peracarid crustaceans, and mollusks) could be damaged or killed by sediment disruption caused by the movement of the tubing; others would merely be temporarily dislodged.

Another potential effect of tubing movement would be the leveling of small-scale sediment features created from movement, feeding, and defecation by sediment-dwelling animals. Such features often persist in the deep sea because of the sluggish currents found at depth, and may provide locally important habitat diversity for infaunal invertebrates. The obliteration of such features is a commonly reported effect of trawling by commercial fishing boats, whose activities impact vast tracts of the seafloor in many regions of the world's oceans.

Complete recovery of hard and soft substrate fauna following tubing disturbance would likely require months to several years. Because tubing disturbance would not cause complete defaunation of the area impacted, recovery rates would likely be more rapid than if the seafloor were completely denuded.

#### **4.3.2.1.4 Miscellaneous Effects**

Other activities during the *Field Experiment*, such as the emplacement and operation of the acoustic net and instrument packages, the collection of seafloor samples for bacteria, introduction of tracer dyes, and the operation of the ROV or submersible, are routinely conducted during research programs

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<sup>14</sup> Radioactive substances would not be used in any of the experiments.

throughout the oceans. The instrument mooring anchors would occupy a very small area and would be composed of non-toxic materials (concrete or iron). After the instrument packages are retrieved at the end of the *Field Experiment*, the remaining anchors would provide hard-substrate outcrops, which could harbor colonizing benthic organisms. These activities would not have a substantial effect on seafloor communities.

#### 4.3.2.2 Anticipated Deep to Midwater Effects

##### 4.3.2.2.1 Direct Deep to Midwater pH Effects

Invertebrate zooplankton have no means of detecting or avoiding the plume of reduced-pH water that the *Field Experiment* would produce and thus could be affected by testing. As previously discussed, a pH of 6.5 may be considered as the threshold above which no effect would be anticipated; a pH below 6.5 could stress or kill some zooplankton if exposure is sufficiently long. The volume of the plume having a pH below 6.5 (less than 10,000 cubic meters for the maximum-release-rate/low-current simulation and 1,000 cubic meters for the maximum-release-rate/high-current simulation) represents the maximum size of the zone of potential effect for one discharge.

The greatest concentrations of zooplankton generally occur within 800 feet (250 meters) of the surface. Copepods have sometimes been observed in high concentration at depths of 1,300 to 2,300 feet (400 to 700 meters; Davis and Wiebe 1985, Longhurst 1985, Beckman 1988). At the expected depth of the bulk of the plume (2,700 to 3,000 feet, or 800 to 900 meters) zooplankton density would be expected to be very low.

Combining the small likelihood that the reduced pH would be of sufficient magnitude and duration to adversely affect zooplankton with the fact that the zooplankton density at the affected depth would be very low, the likelihood of substantial adverse effects on these animals would be minimal.

Some studies have indicated fish and nektonic shrimp react to and avoid water with sub-lethal pH levels (Portman 1970, Davies 1991). If these results are typical of organisms at the *Field Experiment* site, then the *Field Experiment* should harm few fish and nektonic decapods because they would reverse direction upon encountering the plume. Scientists do not know if squid have the same ability to detect low pH water. Investigations by Shirayama *et al.* (1999) indicate that fish that swim extremely close to (i.e., within a few feet of) the discharge nozzle and remain there for some time, could be killed.

Species of concern to the sport-fishing community include representatives from several families including, but not limited to, snappers (Lutjanidae, discussed below in this section), pomfrets (Bramidae, including monchong-*Taractichthys steindachneri* and *Eumegistus illustris*), jacks (Carangidae, including *halahala Trachiurops crumenophthalmus*, *lai-Scrombroides sancti-petri*, *kamanu- Elegatis bipinnulatus*, *ulua- Caranx cheilio*, and *ulua kihikihi- Alectis ciliaris*), dolphins (Coryphaenidae, including *mahi-mahi- Coryphaena lippurus* and *Coryphaena equisetis*), mackerels and tunas (Scombridae, including *ahi- Thunnus albacares*, *ahi palaha- Thunnus alalunga*, *aku-Katsuwonus pelamis*, *akule- Trachiurops*, *kawakawa- Euthynnus affinis*, *ono- Acanthocybium solandri*, *opelu- Decapterus pinnulatus*, and *po'onui- Thunnus obesus*), swordfishes (Xiphiidae, such as the *a'uku- Xiphias gladius*), and billfishes (Istiophoridae, including *a'u- Makaira nigricans* and *Makaira indica*).

The depth ranges are not precisely known for all of the species of interest to local anglers, but depth data for several species from time-depth recorders and observations are available and are discussed below. The centers of distribution of the families listed above occur well above the CO<sub>2</sub> release depth. Some species may occasionally descend to a depth at which they might encounter the plume, but it is unlikely that the experiment would result in any substantial mortality to these sport-fishes. The depth is simply too great and the persistence of sub pH 6.5 water too short.

## AFFECTED ENVIRONMENT &amp; ENVIRONMENTAL CONSEQUENCES

- Block *et al.* (1992) found that blue marlin fish equipped with depth and temperature transmitters exhibited a preference to remain in the surface mixed layer (above the thermocline). One fish was found to remain near the surface in 81° F (27° C) water during daylight hours and make numerous dives between 160 and 330 feet (50 and 100 meters) at night.
- Studies using ultrasonic depth telemetry recorders off the west coast of Hawai'i on yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*), blue marlin, and striped marlin, suggest that these species limit their vertical movements to remain in waters within 14° F (8° C) of surface water temperatures (Brill *et al.* 1993, 1998). Brill *et al.* (1998) reported that five tagged yellowfin tuna remained shallower than 330 feet (100 meters) 80% of the time and shallower than 400 feet (125 meters) 90% of the time. A similar study found that blue and striped marlin spent 85% of the time at depths shallower than 300 feet (90 meters) and limited their descent to a maximum depth of <560 feet (170 meters; Brill *et al.* 1993).
- Bigeye tuna and swordfish reportedly forage routinely to depths as great as 1,600 feet (500 meters) (Carey 1990). This water depth is above the expected upper margin of the area affected by the *Field Experiment*.
- Six species of *lutjanids* (snappers) are found in Hawaiian waters. These include *uku* (gray job fish or gray snapper; *Aprion virescens*), *gindai* (also known as *ukiuki* or Brigham's or flower snapper; *Pristipomoides zonatus*), *to'au* (blacktail snapper; *Lutjanus fulvus*), *ta'ape* (blue striped snapper; *Lutjanus kasmira*), *ehu* (squirrelfish snapper; *Etelis carbunculus*), and the Spotted rose snapper (*Lutjanus guttatus*). These fishes are found above 1,000 feet (300 meters; Haight 1989). Hence, they would not be expected to encounter waters with depressed pH.
- Similarly the deep snappers and other bottom fish such as *ula ula* (*onaga* or long red tail snapper; *Etelis coruscans*), *opakapaka* (pink snapper; *Pristipomoides microlepis*), *kalekale* (Von Siebold's snapper; *Pristipomoides sieboldii*), and the *hapu'upu'u* (the Hawaiian grouper; *Epinephelus quernus*) are not generally found in water depths deeper than 1,000 feet (Fresh Island Fish Company 2000; DLNR-DAR 2000).

The deep-scattering layer is composed primarily of species that migrate to surface waters at night and to depth during the daytime (the aforementioned snappers are generally associated with the seafloor, not the open water that would be above the platform). The deep-scattering layer occurs between 300 and 1,600 feet (100-500 meters). The daytime depth of different species is determined by their center of distribution and swimming speed. Swiftly swimming animals would be able to descend to deeper depths during the day than the slowly swimming species that exist in the same depth range at night. Throughout much of the world's oceans, the deep-scattering layer is composed largely of euphausiids, sergestid shrimps, small bathypelagic fishes, squids, and copepods. The *Field Experiment* would not affect water visited by organisms found in the deep-scattering layer.

#### 4.3.2.2.2 Threatened and Endangered Species

The threatened or endangered species in the vicinity of the planned *Field Experiment* are all air-breathers (reptiles and mammals) that are not normally found at depths that would experience changes in water quality. Even if they were to reach such depths, their need to return to the surface to breathe would severely limit the time during which they would be exposed to reduced pH. In addition, because they are air breathing, CO<sub>2</sub> would not be exchanged across their respiratory membranes. The pH levels of the *Field Experiment* would not be expected to be caustic to their body surfaces because of the relatively low expected acidity and persistence. Hence, they would not be affected unless they directly ingested the CO<sub>2</sub> droplets or exposed their eyes very close to the nozzle; neither is even remotely likely.

#### 4.3.2.2.3 Deep to Midwater Tubing Effects

The vertical segment of tubing that would pass through the deep-to-midwater zone would result in effects similar to those created by a Fish Aggregation Device (FAD) mooring line. The tubing is not expected to have a deleterious effect on marine organisms.

#### 4.3.2.2.4 Other Deep to Midwater Effects

Other effects could result from the movement of a remotely operated vehicle (ROV) or submersible within the study area and the use of acoustical navigational aids. Procedures and techniques for these types of activities have been used without any apparent negative effects during the course of thousands of oceanographic investigations.

### 4.3.2.3 Surface-Layer Effects

#### 4.3.2.3.1 Direct CO<sub>2</sub> Effects on the Surface Layer

As planned, the experimental injection of CO<sub>2</sub> would not be expected to cause any measurable changes in pH or CO<sub>2</sub> concentrations at depths shallower than about 2,000 feet (600 meters). Thus, no impacts on biota or habitats in the surface layer of the ocean, 0 to 650 feet (0-200 meters), is expected. Coral reefs and reef fish communities (including such species as *uhu*- Scaridae species, *Lauwiliwilinukunuku-‘oi‘oi- Forcipiger Longirostris*, and many others) would not be affected by the *Field Experiment*. Similarly, nearshore ecosystems familiar to divers and hosting such species as manta rays (*Manta birostris*) are too remote from the *Field Experiment* site to have the potential to suffer any adverse effects.

#### 4.3.2.3.2 Other Surface Layer Effects

The various operations conducted in the surface layer during the experiment (e.g., running support vessels, platform lowering and raising, ROV or submersible operation, transponder nets) are similar, or identical, to oceanographic research operations repeatedly conducted in Hawaiian waters. No unusual (or measurable) impacts to the biota or habitats of the surface ocean are expected to result from these activities. Concern has been expressed regarding the potential effects of ships and transponders on dolphin activity. The auditory systems of sonar using Odontoceti are adapted for the high ultrasonic frequencies that these animals employ for echolocation. The auditory system of these animals is necessarily robust in that, within milliseconds of producing loud sounds, they receive and process very faint echoes (Au *et al.* 1997, Richardson *et al.* 1995). Responses by cetaceans to the vessels used in this study would not be expected to differ from their response to other similarly sized vessels in Hawaiian waters. It is possible that the activities carried out for the *Field Experiment* could attract dolphins to the site, thereby slightly increasing their normal density in the area.

While highly unlikely, collision with the ships or discharge pipe used for the experiment could harm these organisms. Pipe collision would be particularly unlikely especially for the sonar capable Odontoceti. Ship collision is a known source of mortality for sea turtles and marine mammals, but usually only when the ships are underway. Spotters will be on duty during the ship transits to help minimize the potential for such collisions.

#### 4.3.2.4 “Worst-Case” Accidental Release

The nature of possible accidental releases is discussed in Section 4.2.4. The potential biological impacts are discussed below.

#### 4.3.2.4.1 “Worst-Case” Accidental Release from Tubing Rupture at the Surface

In the worst case scenario of a rupture or break in the tubing at or near the ocean’s surface, nearly all of the CO<sub>2</sub> in the pipe would vaporize into the atmosphere<sup>15</sup> and have virtually no effect on pH or marine biota.

#### 4.3.2.4.2 “Worst-Case” Accidental Release from Tubing Rupture Near the Seafloor

If the tubing fails near the seafloor, the entire volume of CO<sub>2</sub> in the tubing could rapidly discharge. Due to the relatively small volume of CO<sub>2</sub> that would be contained in the tubing, the effects would be much more limited in scale than those previously described for planned tests.

#### 4.3.2.4.3 Other Potential Accidents

The risks and potential impacts from other accidents (e.g., associated with vessel, ROV and submersible operation) would be similar to those potentially resulting from any of many research expeditions conducted regularly in Hawaiian waters.

### 4.3.2.5 Response to Accidental Releases

Shipboard personnel would be briefed on the characteristics and risks associated with the high pressure CO<sub>2</sub> system. At the first indication of an unintentional release, the CO<sub>2</sub> holding tank would be secured and remedies to the situation would be implemented, as appropriate. If any spills of petroleum products occur from vessels used for the *Field Experiment*, the U.S. Coast Guard would immediately be notified.

### 4.3.2.6 Summary of Effects on the Ecosystems at the N\_wiliwili Disposal Site

The overall impact of the *Field Experiment* on the ecosystem of the area would be extremely small. Traces of CO<sub>2</sub> would be expected to be undetectable in the water column within 6 hours; evidence on the deep sea floor would disappear within months to a few years. Some mortality of small midwater organisms may result from CO<sub>2</sub> effects (pH below 6.5). This entire impacted volume would be below a water depth of 500 m (i.e., it would be restricted to the deep ocean where biomass levels are extremely low). Because of the open and dynamic nature of pelagic ecosystems, it is expected that any measurable effects on the midwater biota would dissipate to undetectable levels within hours.

Impacts to the seafloor from the *Field Experiment* would be more persistent than those in the water column, with seafloor community recovery possibly requiring years. The potential seabed area impacted would be so small that no significant impacts to the general ecosystem are conceivable. For example, the ranges of species and populations of all seafloor organisms potentially impacted by the *Field Experiment* would include slope regions on many (most likely all) of the Hawaiian Islands, so the chances of significant population or species level stress would be miniscule. There is no ecological evidence that anticipated small disturbances to the local ecosystem, such as would result from the *Field Experiment*, would result in permanent (or long-term) ecosystem changes.

### 4.3.3 NO ACTION ALTERNATIVE

If the *Field Experiment* was not carried out, no changes in existing marine life, such as those that could be created by conduct of the experiment, would occur. If the *Field Experiment* was conducted at a location not requiring EPA approval, then the effects on marine life would be similar to those presented for the N\_wiliwili Disposal Site.

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<sup>15</sup> This would not constitute discharge of a regulated air pollutant.

## 4.4 EFFECTS ON HISTORIC AND CULTURAL RESOURCES

### 4.4.1 N\_WILIWILI DISPOSAL SITE

The bottom area on which the platform and about 1,000 feet (300 meters) of tubing would rest during the course of each test was explored in October 2001 using a video camera mounted on a remotely operated vehicle. Images were captured for several hours. The area was also investigated extensively using bottom cameras when it was designated as an ocean dumping site by the U.S. Army Corps of Engineers (COE, 1977a and 1977b). No physical historic or cultural remains of any kind were visible within the survey area. The absence of such remains is not surprising, particularly in view of the great depth and the absence of any folklore or other information that might indicate the presence of a shipwreck.

### 4.4.2 NO ACTION ALTERNATIVE

If the *Field Experiment* was not carried out, no effects on historic and cultural resources or traditional uses would occur. If the *Field Experiment* were conducted at a foreign location not requiring EAP approval, then the effects on historic and cultural resources or traditional uses would be similar to those presented for the N\_wiliwili Disposal Site.

## 4.5 EFFECT ON AIR QUALITY & CLIMATE

### 4.5.1 PROJECT ELEMENTS WITH POTENTIAL TO IMPACT CLIMATE OR AIR QUALITY

#### 4.5.1.1 Vessel Operations

The vessels used in the *Field Experiment* would produce air emissions from their power plants. These vessels would comply with appropriate U.S. regulations, as well as the Diesel Engine Requirements contained in Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78).

#### 4.5.1.2 Planned Experimental Emissions and Releases

None of the liquid CO<sub>2</sub> discharged on the seabed is expected to escape into the atmosphere. Hence, the planned releases associated with the *Field Experiment* do not have the potential to affect air quality. The more important aspect of the *Field Experiment's* potential effect on air quality is associated with the contribution that the experiment would make to an understanding of the ability of the oceans to assimilate anthropogenic CO<sub>2</sub>. As previously discussed in Sections 2.1 through 2.3, the fundamental purpose of the *Field Experiment* is to investigate at a small-scale one potential method for mitigating the potential climatic effects of atmospheric emissions of CO<sub>2</sub>.

#### 4.5.1.3 Accidental Releases & Discharges

If the discharge tubing ruptures near the sea surface, a maximum of about one metric ton (1.1 short ton) of CO<sub>2</sub> could potentially be released to the atmosphere over a short period. Possible effects of this release are discussed below (Section 4.5.2.3). If the rupture occurs deeper, the CO<sub>2</sub> would not reach the surface and would not, therefore, affect air quality.

### 4.5.2 AIR QUALITY & CLIMATE EFFECTS AT THE N\_WILIWILI DISPOSAL SITE

#### 4.5.2.1 Effect of Vessel Operations

The air emissions from the research vessels would be a very small percentage of the emissions expected from the normal vessel traffic in the area. The emissions from the research vessels would have no substantial effect on air quality.

#### 4.5.2.2 Anticipated Effects of the *Field Experiment*

As noted above, none of the CO<sub>2</sub> released during the planned *Field Experiment* would reach the surface. Instead, the CO<sub>2</sub> would be expected to dissolve completely into the deep seawater and not affect air quality.

#### 4.5.2.3 Potential Effects of Accidental Releases & Discharges

As discussed in Section 4.5.1.3, an accidental rupture of the discharge tubing could release about 1.6 cubic yards (1.25 m<sup>3</sup>, approximately 1 metric ton) of CO<sub>2</sub> at the surface. If this release would occur on the ship, CO<sub>2</sub> would vent under high pressure, dispersing rapidly. This quantity is too small to have an adverse effect on general air quality. Hence, the only real concern is for a slow leak that would allow CO<sub>2</sub> to build up without awareness by the ship's crew. Standard precautions taken in maintaining and monitoring high-pressure tanks aboard a ship are sufficient to reduce this threat to a minor level.

#### 4.5.3 NO ACTION ALTERNATIVE

If the *Field Experiment* was not carried out, then no effects on air quality would occur. If the *Field Experiment* was conducted at a location not requiring EPA approval, then the effects on air quality would be similar to those presented for the N\_wiliwili Disposal Site.

### 4.6 NOISE AND VIBRATION EFFECTS

#### 4.6.1 PROJECT ELEMENTS WITH POTENTIAL TO CAUSE NOISE AND VIBRATION

##### 4.6.1.1 Vessel Operation and Oceanographic Data Acquisition

Noise would be generated from research vessels used during the *Field Experiment*. Diesel generators and ships' engines, winches and other handling gear, ROV or submersible servos and electric motors, and acoustic telemetry devices would all create noise during conduct of the *Field Experiment*.

Open ocean ambient noise levels range from 74 - 100 dB (broadband power levels in 20 - 1,000 Hz, reference 1 µPa @ 1 m; Federation of American Scientists, 1998). Sound energy measured from a purse seiner fishing boat, a vessel likely to be of similar size to the research ships to be used in the *Field Experiment*, was 120 dB while underway, concentrated below 2 kHz with a strong peak at 360 Hz. Noises from other equipment associated with the *Field Experiment* would be emitted at lower decibel levels. Normal noise levels from speedboats reach 120 to 125 dB with the strongest peak at about 2 kHz. Propeller boats at chase speeds cause the sound to pulsate and to reach a maximum of 130 dB (Awbrey *et al.* 1977). The speedboat sound levels are likely to be similar to the recreational and fishing boats to be expected in the area. A tug pulling a fully loaded barge into N\_wiliwili Harbor (an event that occurs regularly in this area) might have a source level of about 170 dB (Richardson *et al.* 1995).

##### 4.6.1.2 Experimental Discharge

The CO<sub>2</sub> discharge would not produce high levels of noise, either on the sea-surface site or at the seafloor discharge site, since the release would consist of a liquid being discharged into another liquid medium. The acoustical energy produced by these activities would consist principally of noise from vibrations of the nozzle, extension and recovery of the tubing, and operation of surface valves and pumps associated with the delivery of liquid CO<sub>2</sub> to the seafloor.



#### **4.6.2 NOISE & VIBRATION EFFECTS AT N\_WILIWILI DISPOSAL SITE**

##### **4.6.2.1 Vessel and Oceanographic Data Acquisition**

The activities carried out by the research vessels while acquiring oceanographic data would consist of standard practices that are carried out commonly by research ships worldwide. The engine and equipment noises and the acoustic telemetry systems would all produce relatively low-level sounds that would not carry far through seawater or air. These sounds would be comparable to the noises made by fishing vessels, cargo vessels, and other ships that commonly pass through the area. The noise levels would not be audible on land, and they would not be of the magnitude that has been observed to disturb marine organisms.

##### **4.6.2.2 Experimental Discharge**

The high frequency, low-intensity sounds expected from the discharge system would only be audible within a few hundred yards of the discharge site. Marine life within the immediate vicinity of the discharge would not be expected to be adversely affected by the temporary presence of this noise.

#### **4.6.3 NOISE & VIBRATION EFFECTS: NO ACTION ALTERNATIVE**

If the *Field Experiment* is not carried, no noise or vibration effects would occur. If the *Field Experiment* were conducted at a location not requiring EPA approval, then the noise and vibration effects would be similar to those presented for the N\_wiliwili Disposal Site.

### **4.7 EFFECTS ON TRANSPORTATION FACILITIES**

#### **4.7.1 PROJECT ELEMENTS WITH POTENTIAL TO AFFECT TRANSPORTATION FACILITIES**

##### **4.7.1.1 Mobilization and Construction**

Fabrication of the tubing, discharge platform and associated deployment machinery would take place at suitably equipped manufacturing facilities. Custom pieces of equipment, such as the discharge platform and other necessary hardware, would be shipped to a staging port for assembly and checkout before being loaded onto the vessels. All shipping would be via commercial carriers. The staging port would be selected to minimize transportation, storage, and vessel transit and lease costs. The port would be equipped with lifting equipment adequate to stage the materials dockside. Loading onto the ships would be accomplished using either dockside cranes or the handling gear aboard the vessels.

##### **4.7.1.2 Experimental Activities**

Vessels deploying the discharge platform, tubing, and ROV or submersible would have restricted mobility for periods as long as a few days while the platform would be deployed, checked out, and operated. These ships would observe the standard practice of showing the proper signal flags and lights to communicate their situations during these periods. While on site, the vessels would be serviced as necessary only by small craft running in and out from N\_wiliwili Harbor. These service calls would be expected to be limited to necessary transfers of personnel and delivery of emergency replacements.

#### **4.7.2 TRANSPORTATION AT N\_WILIWILI DISPOSAL SITE**

##### **4.7.2.1 Mobilization and Construction**

Mobilization and construction activities are expected to take place at a remote site properly equipped and established to carry out the necessary fabrication, handling, and checkout activities. Because the needed facilities already exist and the needed activities would be part of the normal course of business at those facilities, only minor effects are expected to result.

#### 4.7.2.2 Experimental Activities

The *Field Experiment* would be carried out over two weeks or less. The site would not be in a constricted navigation channel or a major shipping route. Fishing boats use the area where the experiment would be conducted. The movement of fishing boats and other vessels operating in the area would be constrained slightly by the need to provide suitable clearance around the research vessels during deployment of the platform. This would not prevent fishing boats and other vessels from carrying out most of their normal activities.

#### 4.7.3 NO ACTION ALTERNATIVE

If the *Field Experiment* is not conducted, no transportation effects will occur. If the *Field Experiment* were to be conducted at a location where EPA approval is not required, then the transportation effects would be similar to those presented for the N\_wiliwili Disposal Site.

### 4.8 EFFECTS ON LAND USE

#### 4.8.1 N\_WILIWILI DISPOSAL SITE

The *Field Experiment* would be conducted using vessels operating well offshore. The limited shore side activities (e.g., project administration) would be conducted using existing facilities. Consequently, no measurable effects on land use would occur from conducting the *Field Experiment* within the N\_wiliwili Disposal Site.

#### 4.8.2 NO ACTION ALTERNATIVE

If the *Field Experiment* is not conducted, no effects on land use will occur. If the *Field Experiment* were to be conducted at a location where EPA approval is not required, then the land use effects would be similar to those presented for the N\_wiliwili Disposal Site.

### 4.9 AESTHETIC EFFECTS

The *Field Experiment* would not alter landscape or other visual amenities on the land. The vessels conducting the *Field Experiment* would operate well offshore. Consequently, the *Field Experiment* does not have the potential to cause aesthetic impacts.

### 4.10 SOCIOECONOMIC IMPACTS

#### 4.10.1 PROJECT-RELATED EMPLOYMENT AND BUSINESS ACTIVITY

About \$2.4 million U.S. dollars would be directly expended in the State of Hawai'i for conduct of the *Field Experiment* at the N\_wiliwili Disposal Site. About \$2 million from this total would be devoted to labor salaries, services, local researchers' activities, and administrative expenses. In addition, out-of-state expenditures would be made for purchasing some materials (e.g., the tubing).

#### 4.10.2 ADEQUACY OF EXISTING LABOR SUPPLY AND SUPPORT BUSINESSES

Scientific and ship personnel staffing the *Field Experiment* would be employed at existing institutions and organizations. Local businesses would possess more than sufficient capacity to provide the support services that would be needed for any of the alternatives under consideration.

#### 4.10.3 OTHER SOCIOECONOMIC EFFECTS

As discussed elsewhere in this chapter, the *Field Experiment* does not have the potential to affect the fish on which the fishing industry depends and would not constrain fishing activities, except for a short time in the immediate vicinity of the research vessels. Consequently, the *Field Experiment* is not expected to affect the industry adversely.

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Because the *Field Experiment* would not affect the shoreline or nearshore waters, it would not impact shoreline fishing, SCUBA diving, snorkeling, or swimming. The *Field Experiment* would be only of a short duration in a very limited area, and it would not have a substantial effect on sailing or charter boat operations.

Currently, there are no other active ocean-based research programs with the potential for conflict with the *Field Experiment* in the N\_wiliwili Disposal Site, and the *Field Experiment* would not be expected to have any effect on other uses of the site.

#### **4.11 EFFECTS ON PUBLIC FACILITIES AND SERVICES**

##### **4.11.1 PROJECT-RELATED NEED FOR PUBLIC FACILITIES & SERVICES**

In general, the *Field Experiment* would not require the use of any public facilities or services. The only possible exception could occur in the event of a shipboard accident that would require medical treatment. In the unlikely event of such an accident, the type of physical injury that would be expected would almost certainly be similar to injuries that occasionally occur during ship operations. Examples include fractures, contusions, and sprains.

##### **4.11.2 PUBLIC FACILITIES AND SERVICES EFFECTS**

Existing Lihue, Kaua'i medical facilities are equipped to stabilize patients with injuries of the kinds that could occur during the *Field Experiment* and to provide the care needed until patients could be released or transferred to a larger medical facility for specialized care. Air transport that might be needed to carry patients with severe injuries to the large metropolitan hospitals on O'ahu would be available.

##### **4.11.3 PUBLIC FACILITIES AND SERVICES EFFECTS: NO ACTION ALTERNATIVE**

If the *Field Experiment* is not conducted, no effects on public facilities and services can occur. If the *Field Experiment* were to be conducted at a location where EPA approval is not required, then the effects on public facilities and services effects would be similar to those presented for the N\_wiliwili Disposal Site.

#### **4.12 PUBLIC AND WORKER SAFETY & HEALTH**

##### **4.12.1 OVERALL WORKER HEALTH AND SAFETY ISSUES**

None of the activities that would be conducted during the *Field Experiment* have the potential to affect the general safety of the public.

With respect to worker safety, fabrication of the platform, CO<sub>2</sub> storage tank, and tubing that would be used to deliver the CO<sub>2</sub> to the seafloor, and other experimental equipment would involve medium-to-heavy industrial activities. These activities would be carried out in facilities with the proper equipment and procedures, and the contractors would be required to comply with applicable Occupational Safety and Health Administration (OSHA) regulations and other workplace requirements. None of the required manufacturing or assembly activities would be unusually dangerous or hazardous. The CO<sub>2</sub> required for the experiment would be the same type used in many industries and hospitals, would be purchased from existing suppliers, and would not require unusual activities or delivery procedures. Hence, little potential for adverse effects on worker safety and health would result.

Because of the motions imparted by ocean waves, limited on-deck space, and other factors, activities carried out at sea are inherently more dangerous from the viewpoint of worker safety than the same activities carried out on land. The operators of the research vessels are accustomed to these risks,

however, and would typically require stringent training and safety procedures designed to minimize the additional risk.

#### **4.12.2 SAFETY ISSUES RELATED TO *FIELD EXPERIMENT*-SPECIFIC ACCIDENT AND RELEASE**

##### **4.12.2.1 CO<sub>2</sub> Storage Tank**

While the liquid CO<sub>2</sub> would be stored under relatively high pressure, the pressure level would be well within the range for tanks commonly used for regular industrial and recreational activities. A SCUBA tank, for example, stores air at approximately 2,300 pounds per square inch, or about seven times the pressure of the CO<sub>2</sub>. Thus, the potential for a catastrophic failure is remote.

If a slow leak were to develop, the transformation of CO<sub>2</sub> from a liquid to a gas would cool the area around the leak, possibly even causing ice to form, which would draw immediate attention to the leak. Hence, there would be little likelihood that CO<sub>2</sub> could escape unnoticed. Even if a leak was to go unnoticed, the fact that the tank would be stored on deck in the open air means that the CO<sub>2</sub> would not collect in occupied spaces. Instead, the CO<sub>2</sub> (which is heavier than air) would spill over the deck and eventually disperse into the atmosphere. Consequently, a storage tank leak would not constitute a significant hazard to shipboard personnel.

##### **4.12.2.2 Tubing Failure**

If the tubing were to fail catastrophically, the escaping CO<sub>2</sub> could act as a jet, moving the tubing about violently. If a break would occur well below the surface of the ocean, the drag of the water would attenuate the motion of the tubing to the point where it would not be a concern. Consequently, the greatest safety hazard would arise from a possible break several tens of feet from the ship. In this case, gas escaping from the tubing could whip the tubing about, possibly causing an impact to equipment or people on the deck of the ship.

This type of hazard would be similar to the movement that would occur if a cable breaks under tension (as would occur if a line used by a tug to pull a barge breaks). Crews routinely take precautions to keep deck space clear of unnecessary activity under such circumstances, which would reduce the potential for injury. The system used for the *Field Experiment* would minimize the possibility of injury from such an accident by having an automatic cutoff valve that would immediately terminate the flow of CO<sub>2</sub> into the pipe if a rapid depressurization occurs.

#### **4.13 BIODIVERSITY AND ENVIRONMENTALLY SENSITIVE RESOURCES**

While ocean waters are considered sensitive environments, as discussed in previous sections of this chapter, the *Field Experiment* would be conducted in (and would affect) a subsurface area that does not contain especially sensitive resources. The activities required for conducting the *Field Experiment* would also not have an adverse effect on biodiversity.

The *Field Experiment* would be conducted well offshore and at a depth of approximately 3,000 feet (900 meters). The changes in water quality that would result from the experiment would be undetectable above a depth of approximately 2,000 feet (600 meters) and then only close to the *Field Experiment*. Reef-building corals are limited to water depths far above this; hence, no adverse effect on reef-building corals would be possible. Most deep-sea precious corals also occur only at depths above 500 meters. Some, such as the pink coral (*Corallium secundum*), are found at this depth and below. No precious corals have been seen during the submersible and ROV inspections of the site. Consequently, the *Field Experiment* would have no potential to affect deep-sea precious corals and would be consistent with the provisions of Executive Order 13089: Coral Reef Protection (see Section 6.1.8).

The *Field Experiment* would take place outside the 100-fathom isobath and beyond the southernmost limit of the Hawaiian Islands Humpback Whale National Marine Sanctuary. As discussed in Section

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0, the CO<sub>2</sub> that would be released during the *Field Experiment* would only affect water quality at substantial depths, and the plume would not travel sufficiently far from the point of release to enter the Sanctuary. This means that there would be no potential for substantial adverse effect on the Sanctuary habitat or Humpback whales themselves (see Section 6.1.9).

Over the long term, the information that the *Field Experiment* would be designed to collect would assist in providing a better understanding of the ability of the oceans to assimilate anthropogenic CO<sub>2</sub>. This information could be critically important in identifying and developing measures that could slow or prevent anthropogenic climate change. Unchecked, such changes would have far greater potential to reduce biodiversity and disrupt environmentally sensitive resources than would the *Field Experiment*.

#### **4.14 ENVIRONMENTAL JUSTICE**

##### **4.14.1 APPLICABLE REQUIREMENTS (EXECUTIVE ORDER 12898)**

Executive Order 12898 is intended to make achieving environmental justice part of the mission of Federal agencies by requiring agencies to identify and address, as appropriate, the potential for disproportionately high or adverse human health or environmental effects on minority or low-income populations.

##### **4.14.2 COMPLIANCE SUMMARY**

The *Field Experiment* would be conducted well offshore in deep ocean waters. No minority populations reside in the area. Members of minority groups probably do occasionally fish within the Ocean Research Corridor and might fish at another ocean site. The *Field Experiment* would not involve activities that would have an adverse effect on persons in the area. In view of the foregoing, the *Field Experiment* would be consistent with Executive Order 12898. No disproportionately high or adverse effects on minority or low-income populations would result from the proposed action.

#### **4.15 SUMMARY OF POLLUTION PREVENTION MEASURES**

##### **4.15.1 FEATURES INCORPORATED IN THE FUNDAMENTAL EXPERIMENTAL DESIGN**

Efforts to minimize the potential for pollution began at the outset of defining the concepts for a *Field Experiment* and have continued throughout the evaluation and definition of those concepts. The goal of these efforts was to identify pollution-limiting approaches and to integrate these approaches into plans for the *Field Experiment*. To achieve this goal, the following tenets were established:

- The experiment would be designed to use the smallest possible amount of CO<sub>2</sub> consistent with achievement of the scientific objectives. Thus, the 44-66 short tons (40-60 metric tons) included in the preliminary plan for the experiment was considerably less than the amount (100 to 300 metric tons) initially considered as being required to achieve scientific objectives. The total release volume now proposed (approximately 20 tons) is even smaller.
- The duration of the experiment has been shortened from the month-long series of tests that was originally envisioned to 10 to 14 days.
- Individual test releases of CO<sub>2</sub> would be limited to the smallest rates and the shortest durations (2 hours) possible while still providing some assurance that the required scientific measurements could be made. The maximum release rate now proposed (9.5 gallons eper minute) is 40 percent less than the rate originally proposed.

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- The experimental concept would include consideration of an advanced, vessel-based deployment system that would eliminate the need to construct and operate a pipeline through a nearshore environment.
- Test facilities used for the experiment would be completely removable at the conclusion of the testing.

**4.15.2 ADDITIONAL POLLUTION PREVENTION MEASURES**

The computer modeling that has been done by scientists from around the world using a variety of computer models and data sources provides reasonable assurance that the water quality effects of the experiment would fall within the predicted envelope. As with any enterprise designed to expand scientific understanding of natural processes, some uncertainty remains.

Because of this uncertainty, the experimental plan (see Appendix C) would require real-time monitoring of the releases. While complete details of this monitoring program are still being developed, the program would include items such as: (1) pH monitors to determine if a release reduces pH to a greater or lesser extent than anticipated; and (2) visual observations of the release platform and surrounding waters to indicate if megafauna are being acutely affected by the release.

The experiment would involve the use of a high-pressure system for the CO<sub>2</sub>. Pressure sensors connected to automatic shut-off valves would constantly monitor the system. If an unexpected loss of pressure would be detected, the sensors would send a signal that would immediately close the valves. This would limit the amount of CO<sub>2</sub> that could be released to only slightly more than the amount present in the pipeline.

As previously noted, shipboard personnel would be briefed on the characteristics and risks associated with the high pressure CO<sub>2</sub> system. At the first indication of an unintentional release, the CO<sub>2</sub> holding tank would be secured.

The research ships and the vessel that would deploy the discharge system would notify the U.S. Coast Guard immediately should any spills of petroleum products occur.

Public notices concerning the planned experiment would be published before the beginning of the experiment. Information concerning the timing and nature of project-related ship movements would be included in these notices. If possible, the notices would be posted at the N\_wiliwili Harbor and at other locations from which boat operators might begin operations requiring use of waters near the N\_wiliwili Disposal Site.

## **5.0 CONSISTENCY WITH FEDERAL, REGIONAL, STATE, & LOCAL LAND USE PLANS, POLICIES, & CONTROLS**

### **5.1 N\_WILIWILI DISPOSAL SITE**

#### **5.1.1 CONSISTENCY WITH LOCAL LAND USE PLANS, POLICIES, & CONTROLS**

The N\_wiliwili Disposal Site is outside the jurisdiction of the County of Kaua‘i. Hence, there are no applicable local land use plans, policies, or controls.

#### **5.1.2 CONSISTENCY WITH STATE LAND USE PLANS, POLICIES, & CONTROLS**

The N\_wiliwili Disposal Site is outside the jurisdiction of the State of Hawai‘i. Hence, there are no applicable local land use plans, policies, or controls.

#### **5.1.3 CONSISTENCY WITH FEDERAL LAND USE PLANS, POLICIES, & CONTROLS**

The N\_wiliwili Disposal Site is designated by the U.S. Environmental Protection Agency (EPA) as an ocean dumping site, and it is used primarily for the disposal of dredged materials from the N\_wiliwili Harbor. Dredging activities are sporadic and not likely to conflict with the conduct of the *Field Experiment*. The U.S. Army Corps of Engineers will be contacted after the final scheduling of the *Field Experiment* is completed to ensure that any planned dredged material disposal operations will be accommodated as necessary in the scheduling and execution of the *Field Experiment*.

EPA has ruled that releases such as those that would result from the *Field Experiment* constitute “dumping” and require a “Research Permit” as provided for in 40 CFR Part 220.3(e). The project manager for the *Field Experiment* submitted an application for such a Research Permit to EPA Region IX in May, 2001. The application presents a detailed analysis that shows that the proposed *Field Experiment* is consistent with the uses prescribed for ocean dumping sites.

### **5.2 NO ACTION ALTERNATIVE**

If the *Field Experiment* is not carried out, no concerns about consistency would exist. If the *Field Experiment* would occur without DOE participation, the same consistency criteria for the project site would apply. That is, acceptability of any site would depend on the *Field Experiment* being consistent with the existing land use plans, policies, and controls that apply to that site.

## 6.0 COMPLIANCE WITH OTHER REGULATIONS

### 6.1 FEDERAL REQUIREMENTS

The *Field Experiment* would be planned and conducted in compliance with the National Environmental Policy Act (NEPA). The *Field Experiment* would also be subject to review under several other Federal regulations. These include:

- Section 401 of the Federal Clean Water Act;
- Section 402 of the National Pollutant Discharge Elimination System;
- Department of the Army Permit, for activities subject to regulation under Section 404 of the Federal Clean Water Act and Section 103 of the Marine Protection, Research, and Sanctuaries Act;
- Section 106 of the National Historic Preservation Act of 1966;
- Section 7 of the Endangered Species Act of 1973, as amended;
- Provisions of the Fish & Wildlife Coordination Act; and
- National Invasive Species Act of 1996.

#### 6.1.1 NATIONAL ENVIRONMENTAL POLICY ACT (NEPA)

This Environmental Assessment (EA) has been prepared in conformance with NEPA. The EA was developed through a process of internal and public scoping and consultation with cognizant Federal, State, and local officials. DOE and other project participants also coordinated with resource management agencies and members of the public following publication of a draft EA to determine their concerns. In accordance with the tenets of NEPA, development of concepts for the *Field Experiment* has been substantially modified in response to suggestions that have been received. These changes included suspending consideration of shore-based alternatives that would have required a pipeline through nearshore waters, reducing the anticipated number of pipeline deployments and increasing the ecological monitoring component of the planned tests.

#### 6.1.2 SECTION 401 OF THE FEDERAL CLEAN WATER ACT AND SECTION 402 OF THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM

EPA Region IX has determined that the NPDES does not apply to the *Field Experiment* and will instead regulate the experiment under the authority of the Ocean Dumping Act regulations (40 CFR Part 220.3(e)).

#### 6.1.3 DEPARTMENT OF THE ARMY PERMIT

The U.S. Army Corps of Engineers has determined that the *Field Experiment* would not require a Department of the Army permit.

#### 6.1.4 NATIONAL HISTORIC PRESERVATION ACT OF 1966; NATIVE AMERICAN GRAVES PROTECTION AND REPATRIATION ACT OF 1990

As discussed in Section 4.4, extensive observations of the Disposal site have not identified any cultural or historic resources in the area. The site is well offshore and the *Field Experiment* would not have any impacts on historic resources or native American grave sites.



### 6.1.5 OTHER KEY RULES ADMINISTERED BY THE U.S. FISH & WILDLIFE SERVICE AND THE NATIONAL MARINE FISHERIES SERVICE

In compliance with the Section 7 of the Endangered Species Act and the Fish and Wildlife Coordination Act, DOE consulted with the U.S. Fish & Wildlife Service and with the National Marine Fisheries Service during preparation of the Environmental Assessment. DOE has confirmed that, in conducting the *Field Experiment*, it would comply with the Migratory Bird Treaty Act (16 USC, Section 703 *et seq.*) and with the National Invasive Species Act of 1996 (Public Law 104-332). The *Field Experiment* activities would be short-term, localized, and focused primarily on the deep seabed at water depths of about 2,600 feet. These activities would not substantially affect threatened, endangered, or migratory birds or the marine food chains that help support these species. As outlined in Section 7.1.7, ships used for the *Field Experiment* would comply with all applicable laws and regulations designed to prevent the introduction of exotic species into coastal marine waters.

DOE has contacted the National Marine Fisheries Service (NMFS) concerning potential effects on sea turtles and other listed species under its jurisdiction. Potential effects on Humpback whales are discussed in Section 6.1.9. DOE submitted an Essential Fish Habitat Assessment to the NMFS in accordance with requirements of the 1996 amendments to the Magnuson-Stevens Fishery Conservation and Management Act (Public Law 94-265).

As discussed in Section 4.3.2.2.2, the threatened or endangered species in the vicinity of the planned *Field Experiment* are all air-breathers (reptiles and mammals) that are not normally found at depths that would experience changes in water quality. Even if these animals were to reach such depths, their need to return to the surface to breathe would severely limit the time during which they would be exposed to reduced pH. In addition, because they are air breathing, CO<sub>2</sub> would not be exchanged across their respiratory membranes (see Section 4.3.2.2.2). The pH levels of the *Field Experiment* would not be expected to be caustic to their body surfaces because of the relatively low expected acidity and persistence. Hence, they would be very unlikely to be affected.

Collisions with ships or the transport pipe would be more likely to harm these organisms. Pipe collision would be relatively unlikely especially for the sonar-capable Odontoceti. Ship collision is a known source of mortality for sea turtles and marine mammals, but usually only when the ships are moving. Spotters would be on duty during ship transits to minimize the potential for such collisions.

### 6.1.6 OCEAN DUMPING ACT

The Marine Protection, Research, and Sanctuaries Act of 1972 (Public Law 92-532) has two basic aims: to regulate intentional ocean disposal of materials and to authorize related research. Title I of the Act, which is often referred to as the Ocean Dumping Act, contains permit and enforcement provisions for ocean dumping. Passed in 1972, the Act provides a framework for managing ocean dumping activities and for conducting basic oceanic research. The law bans ocean dumping of radiological, chemical, and biological warfare agents and high-level radioactive wastes. Amendments in 1988 extended this ban to sewage sludge, industrial wastes, and medical wastes. The law provides a mechanism for meeting U.S. commitments under the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters, an international ocean dumping treaty signed by 80 countries. The Act authorizes research on the effects of ocean dumping, pollution, over-fishing, and other human-induced stressors, including oil spills.

The experimental release of CO<sub>2</sub> for scientific research that is proposed as part of the *Field Experiment* has been determined by the EPA, Region IX to fall within the definition of “dumping” as defined in 40 CFR Part 220.2. The project management is pursuing the acquisition of a research ocean dumping permit for conducting the experiment at the EPA-designated N\_wiliwili Ocean Dumping Site.

### 6.1.7 COAST GUARD REGULATIONS

Research vessels for the *Field Experiment* would be equipped with U.S. Coast Guard-approved marine sanitation devices (33 CFR 159) to preclude unauthorized discharges of sanitary wastes. The research vessels would comply with all applicable U.S. Coast Guard safety procedures and required navigational lighting and day shapes for operating vessels in restricted maneuverability and at night. Research vessels would comply with U.S. Coast Guard regulations (33 CFR 151) and other applicable Federal and State of Hawai‘i laws and regulations for the management of bilge and ballast water to minimize pollution and the introduction of non-indigenous or exotic species into U.S. waters.

### 6.1.8 EXECUTIVE ORDER 13089: CORAL REEF PROTECTION

In 1998, the President issued Executive Order 13089: Coral Reef Protection.<sup>16</sup> Its purpose is to preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment. It defines coral reef ecosystems as those species, habitats, and other natural resources associated with coral reefs in all maritime areas and zones subject to the jurisdiction or control of the United States (e.g., Federal, State, Territorial, or commonwealth waters), including reef systems in the south Atlantic, Caribbean, Gulf of Mexico, and Pacific Ocean.

The Executive Order requires Federal agencies whose actions may affect U.S. coral reef ecosystems to:

- Identify actions that may affect U.S. coral reef ecosystems;
- Utilize their programs and authorities to protect and enhance the conditions of such ecosystems; and
- Ensure (to the extent permitted by law) that any actions they authorize, fund, or carry out will not degrade the conditions of such ecosystems.

The *Field Experiment* would be conducted well offshore at a depth between 2,600 and 3,280 feet (800 – 1,000 meters). The changes in water quality that would result from the experiment would be undetectable above a depth of approximately 500 meters and, then, only close to the *Field Experiment*. Reef-building corals are limited to water depths far above this and occur only well beyond distances where dispersion of releases from the experiment could have an effect. No adverse effect on reef-building corals would be possible.

Most deep-sea precious corals also occur only at depths above 500 meters. Some, such as the pink coral (*Corallium secundum*), are found at this depth and below. As discussed in Section 4.1.4.1, no precious coral resources are known to exist near the N\_wiliwili Disposal Site. The *Field Experiment* would have no potential to affect deep-sea precious corals and would be consistent with the provisions of Executive Order 13089: Coral Reef Protection.

### 6.1.9 HAWAIIAN ISLANDS HUMPBACK WHALE NATIONAL MARINE SANCTUARY

The waters around the main Hawaiian Islands constitute one of the world’s most important North Pacific Humpback whale (*Megaptera novaeangliae*) habitats. These waters are the only place in the United States where Humpbacks reproduce. Scientists estimate that two-thirds of the entire North Pacific Humpback whale population (approximately 4,000-5,000 whales) migrates into Hawaiian waters to breed, calve, and nurse. While in Hawai‘i, usually between November and May with a peak season in January and February, Humpback whales are most often found in shallow coastal waters, at depths usually less than 300 feet (~100 meters).

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<sup>16</sup> The Executive Order is intended to support the purposes of various U.S. laws and regulations. These include the Clean Water Act of 1977, as amended (33 USC. 1251, *et seq.*), Coastal Zone Management Act (16 USC. 1451, *et seq.*), Magnuson-Stevens Fishery Conservation and Management Act (16 USC. 1801, *et seq.*), National Environmental Policy Act of 1969, as amended (42 USC. 4321, *et seq.*), and National Marine Sanctuaries Act (16 USC. 1431, *et seq.*).

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COMPLIANCE WITH OTHER REGULATIONS

The U.S. Congress, in consultation with the State of Hawai‘i, designated the Hawaiian Islands Humpback Whale National Marine Sanctuary on November 4, 1992. This designation was finalized with the formal approval by Hawai‘i Governor Ben Cayetano on June 15, 1997. The Hawaiian Islands National Marine Sanctuary Act is intended to:

- Protect Humpback whales and their habitat within the Sanctuary;
- Educate and interpret for the public the relationship of Humpback whales and the Hawaiian Islands marine environment;
- Manage human uses of the Sanctuary consistent with the Hawaiian Islands National Marine Sanctuary Act and the National Marine Sanctuary Act; and
- Provide for the identification of marine resources and ecosystems of national significance for possible inclusion in the Sanctuary.

The National Marine Sanctuary regulations are found at 15 CFR 922. As defined by Section 922.181, the Hawaiian Islands Humpback Whale National Marine Sanctuary consists of the submerged lands and waters off the coast of the Hawaiian Islands seaward from the shoreline, cutting across the mouths of rivers and streams. In the waters off Kaua‘i, the Sanctuary extends along the north shore of the island and is well removed from the N\_wiliwili Disposal Site. The Sanctuary extends from the shoreline to the 100-fathom (600 feet or ~183 meters) isobath.

The regulations make it unlawful for any person to conduct or cause to:

- Approach within 100 yards of any Humpback whale except as authorized under the Marine Mammal Protection Act (MMPA);
- Operate any aircraft above the Sanctuary within 1,000 feet of any Humpback whale except as necessary for takeoff or landing from an airport or runway, or as authorized under the MMPA and the Endangered Species Act (ESA);
- Take any Humpback whale in the Sanctuary except as authorized under the MMPA and the ESA;
- Possess within the Sanctuary (regardless of where taken) any living or dead Humpback whale or part thereof taken in violation of the MMPA or the ESA;
- Discharge or deposit any material or other matter in the Sanctuary;
- Alter the seabed of the Sanctuary; or
- Discharge or deposit any material or other matter outside the Sanctuary if the discharge or deposit subsequently enters and injures a Humpback whale or Humpback whale habitat.

The *Field Experiment* would take place well outside the 100-fathom isobath and beyond the limit of the Hawaiian Islands Humpback Whale National Marine Sanctuary. As discussed in Section 0, the CO<sub>2</sub> that would be released during the *Field Experiment* would only affect water quality at substantial depths, and the plume would not travel sufficiently far from the point of release to enter the Sanctuary. This means that there would be no potential for adverse effect on the Sanctuary habitat or Humpback whales themselves.

#### 6.1.10 OCEANS ACT

The Oceans Act of 2000 (Public Law 106-256; effective date January 20, 2001) was enacted on August 7, 2000, for the purpose of developing a coordinated and comprehensive national ocean policy. Included among the policy objectives that will be pursued under the Act are actions to promote the following:

- Protection of the marine environment and prevention of marine pollution;

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**COMPLIANCE WITH OTHER REGULATIONS**

- Expansion of human knowledge of the marine environment, including the role of the oceans in climate and global environmental change; and
- Preservation of the role of the United States as a leader in ocean and coastal activities and, when in the national interest, cooperation by the United States with other nations and international organizations in ocean and coastal activities.

Policy development activities will be based on equal consideration of environmental, technical feasibility, economic, and scientific factors. Under the Act, a 12-member Commission on Ocean Policy that will be appointed by the President in 2001 will develop policy recommendations. This Commission, in developing ocean policy recommendations, could potentially benefit from technical and environmental information resulting from the proposed *Field Experiment*.

**6.2 STATE REQUIREMENTS**

No State laws or regulations are directly applicable to the *Field Experiment*.

**6.3 KAUA'I COUNTY REQUIREMENTS**

No Kaua'i County ordinances or regulations are directly applicable to the *Field Experiment*.

**6.4 INTERNATIONAL AGREEMENTS**

The N\_wiliwili Disposal Site is within the Territorial waters of the United States and is not directly subject to the provisions of international agreements.

## 7.0 SECONDARY & CUMULATIVE EFFECTS AND LONG-TERM ENVIRONMENTAL CONSEQUENCES

### 7.1 SECONDARY (INDIRECT) EFFECTS

Secondary, or indirect, effects are effects caused by actions that occur later in time or farther removed in distance, but which are still reasonably foreseeable. Indirect effects may include growth-inducing effects and other effects related to induced changes in the pattern of land use, population density or growth rate, and related effects on air and water and other natural systems, including ecosystems.

As described in Chapter 4 of this report, the effects of the *Field Experiment* would be limited to direct short-term perturbations in seawater chemistry and localized impacts on marine biota. The *Field Experiment* would not represent a commitment to larger-scale tests or to actual use of ocean sequestration as a disposal technology. Consequently, no substantial secondary effects are anticipated.

### 7.2 CUMULATIVE EFFECTS

The Council on Environmental Quality's (CEQ) regulations for implementing the National Environmental Policy Act (NEPA) define cumulative effects as the impact on the environment which results from the incremental impact of the proposed action when added to other past, present, and reasonably foreseeable future actions, regardless of what agency (Federal or non-Federal) or person undertakes such other actions (40 CFR, Section 1508.7).

No similar activities have taken place at the N\_wiliwili Disposal Site, no additional similar experiments are planned for that area, and no activities with effects that, when added to the consequences of the proposed action could lead to adverse impacts, are known to be planned by others. Because of this and the fact that the *Field Experiment's* effects would be localized, there would be no potential for cumulative effects at this location.

### 7.3 LONG-TERM ENVIRONMENTAL CONSEQUENCES

The *Field Experiment* is designed to provide needed technical information related to potential mitigation of atmospheric emissions of CO<sub>2</sub>. By itself, the *Field Experiment* would have no long-term environmental consequences. If the *Field Experiment* were completed successfully, it would have the potential of providing policymakers and the public with better capability for judging the feasibility and effectiveness of marine CO<sub>2</sub> sequestration. Such enhanced capability would make it more likely that informed and environmentally beneficial policy decisions could be made than would otherwise be possible without the results from the *Field Experiment*. A discussion of the scientific context for the *Field Experiment* is presented in Appendix D.

## 8.0 IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES

### 8.1 N\_WILIWILI DISPOSAL SITE

The principal natural resources that could be affected by the *Field Experiment* are the deep-sea marine life near the CO<sub>2</sub> release. Some small fraction of the benthic life in this area would be stressed to an important degree, and some mortality is expected, particularly of plankton in the water column. Because of rapid recolonization due to mixing with surrounding waters, the effect on organisms inhabiting the water column would likely be very short. To the very limited extent that the benthos would be affected, recovery to background levels of biomass and diversity would take longer. While substantial effects are not anticipated, the depressed pH level that would result from the CO<sub>2</sub> plume would kill zooplankton and possibly other fauna within a small area. Even under the worst assumptions, most species would recover immediately after the conclusion of the experiment; recovery of even the slowest growing would recover within a period of a few years.

Emplacements of the discharge platform would likely crush or bury the fauna living on and in the underlying seafloor. The disturbed patches are expected to return to pre-experiment conditions in periods ranging from a few weeks to a few years. Disturbance on this scale would not cause any long-lasting negative impacts to any of the seafloor fauna at the population or species level.

As discussed in Section 4.3.2.1.3, additional areas would be impacted by the repeated deployments of the platform and tubing. The effects caused by the tubing moving over the seafloor include the obliteration of small-scale sediment features that result from movement, feeding, and defecation by sediment-dwelling animals. Disruptions of this sort are commonly reported effects of trawling, which affects vast tracts of the seafloor in many regions of the world's oceans. While recovery of hard and soft substrate fauna following disturbances would likely require months to several years, the disturbances would not be permanent.

Resources irreversibly and irretrievably committed to the *Field Experiment* would also include research funds and the time, scientific knowledge, and energy of the individuals involved in carrying out the work. Devoting vessel time to the *Field Experiment* would preclude use elsewhere.

### 8.2 NO ACTION ALTERNATIVE

No commitments of resources would occur if the *Field Experiment* is not conducted. The absence of the scientific knowledge that the planned *Field Experiment* would provide could lead to poor decisions that misuse scarce resources. If the *Field Experiment* were carried out in a location not requiring EPA approval, then the same commitments of resources as required for conduct of the experiment at the N\_wiliwili Disposal Site would be expected.

## **9.0 RELATIONSHIP BETWEEN SHORT-TERM USES AND LONG-TERM PRODUCTIVITY**

### **9.1 N\_WILIWILI DISPOSAL SITE**

The *Field Experiment* would occupy a localized area of the seafloor for a period of two weeks or less. After completion of the *Field Experiment*, the research ships, all instrumentation, and discharge equipment would be removed. If the *Field Experiment* is successful in obtaining the data sought, the results could have important implications for future, long-term policy decisions regarding mitigation of atmospheric emissions of CO<sub>2</sub>.

### **9.2 NO ACTION ALTERNATIVE**

If the *Field Experiment* is not conducted, there would be no effect on the local productivity at the project site. If the *Field Experiment* were carried out at a location not requiring EPA approval, then the local balance between short-term uses and long-term productivity of the environment would be the same as that for the N\_wiliwili Disposal Site. However, the lack of the scientific information that the proposed experiment is intended to provide could lead to poorer resource management decisions. These, in turn, could have an adverse effect on the long-term productivity of the world's ecosystems.

## 10.0 SIMILAR ACTIONS AND ACTIONS BEING CONSIDERED UNDER OTHER NEPA REVIEWS

The proposed action is not similar to any other action being considered by (or currently being implemented by) EPA or other Federal agencies and is not a segment of any other action for which review under NEPA would be required.

Many policy options and technological concepts have been identified as possible approaches to address causes of climate change induced by human activity, including carbon taxes, emission caps and emission trading systems, incentive programs to promote changes to low- or zero-carbon emitting technologies, and a variety of geochemical/engineering concepts for mitigating the warming of the atmosphere. Also, geochemical and engineering concepts for reducing carbon emissions would include options such as use of renewable energy sources or fuel switching, improving the efficiencies of systems for both energy supply and energy utilization, and sequestering carbon.

The U.S. Department of Energy, which is one of the project sponsors, has historically supported research and development projects that focus on creating less carbon-intensive and more efficient methods for generating energy. Although technologies that could result from these activities may help reduce emissions of greenhouse gases, given the importance of developing adequate strategies for mitigating climate change, other approaches, such as carbon sequestration, if successfully developed, may offer additional potential as an option for future consideration in planning strategies for reducing the buildup of greenhouse gases in the atmosphere. As noted in Section 2.2.1, DOE is conducting research to establish an adequate scientific understanding of candidate approaches for carbon sequestration.

DOE has identified several possible concepts to sequester carbon dioxide. However, to validate the feasibility of these options, a knowledge base on the concepts needs to be developed. To establish that knowledge base, research on a variety of concepts must be performed, and such research has been initiated through a number of separate projects to determine the viability of a variety of options for carbon management. The proposed *Ocean Sequestration of CO<sub>2</sub> Field Experiment* is one of those projects.

The purpose of DOE's research on carbon sequestration is to identify and evaluate concepts that could help meet any future challenges potentially resulting from global climate change. This research has been, and continues to be, exploratory in nature, to study the technical merits and to assess the potential economic and environmental consequences of various options for capturing, storing, and reducing emissions of greenhouse gases, particularly carbon dioxide. Sequestration options dealing directly with carbon dioxide can be separated into the following categories of research:

- separation and capture, to identify approaches that could potentially improve greenhouse gas collection and reduce their costs,
- sequestration in geologic formations, to identify and address the technical and environmental potential for sequestering CO<sub>2</sub> in oil and gas reservoirs, coal seams that cannot be mined, and deep saline formations,
- ocean sequestration, to study approaches for injecting CO<sub>2</sub> into deep areas of the ocean, for stimulating natural carbon absorption from the atmosphere, or for converting CO<sub>2</sub> into ocean-stable minerals,
- terrestrial sequestration, to enhance the natural CO<sub>2</sub> absorbing processes of soils and vegetation,
- other concepts, to examine novel chemical or biological methods for converting CO<sub>2</sub> into commercial products or inert, stable compounds, and
- modeling and assessment, to develop improved methods to assess the costs, risks, and potential of various CO<sub>2</sub> sequestration options. These methods would be used to evaluate sufficiently the



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SIMILAR ACTIONS

advantages and disadvantages of research options in order to establish whether or not they warrant further development.

In addition to the proposed *Field Experiment*, the U.S. Department of Energy is providing funds for research on a variety of projects in each of these areas, with each of the separate projects being performed by a university, research institute, DOE laboratory, or industrial organization. Projects are currently being examined in the following areas:

separation and capture

- membrane approach for separating CO<sub>2</sub> from gas streams
- capture of CO<sub>2</sub> from gas streams using chemicals

sequestration in geologic formations

- studies and tests of CO<sub>2</sub> storage in coal seams
- study of saline reservoirs to assess CO<sub>2</sub> storage capabilities and environmental risks
- development of subterranean imaging technology

ocean sequestration

- analysis of natural ocean deposits of CO<sub>2</sub> hydrates on the seafloor
- investigation of analytical techniques to determine long-term fate, biological responses, and sediment effects of CO<sub>2</sub> hydrate in the deep sea

terrestrial sequestration

- evaluation of reclamation and re-forestation approaches that would sequester CO<sub>2</sub> in trees or abandoned mines

other concepts

- evaluation of photosynthetic organisms in specially designed bioreactors for enhancing the rate of CO<sub>2</sub> conversion
- evaluation of species of micro-algae for photosynthesis of CO<sub>2</sub> from power plant exhaust gases

modeling and assessments

- development of a computer model to assess sequestration options and costs
- development of a data base to catalog CO<sub>2</sub> source-to-sequestration information

These research projects are independent elements of DOE's effort to identify potential approaches that could assist in future efforts to control buildup of greenhouse gases in the atmosphere. A variety of approaches are being investigated to assess their technical, economic, and environmental viability. None of these separate research projects, including the proposed *Field Experiment*, is an integral element of an established commercialization plan for the large-scale sequestration of carbon dioxide.

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## 12.0 APPENDICES

**APPENDIX A: PROJECT AGREEMENT FOR INTERNATIONAL  
COLLABORATION ON CO<sub>2</sub> OCEAN SEQUESTRATION**

**APPENDIX B: PUBLIC OUTREACH PROGRAM**

**APPENDIX C: DRAFT EXPERIMENTAL PLAN FOR THE OCEAN  
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**APPENDIX D: CONCEPTS AND MODELS RELEVANT TO THE *FIELD  
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*APPENDIX A: PROJECT AGREEMENT FOR INTERNATIONAL COLLABORATION ON  
CO<sub>2</sub> OCEAN SEQUESTRATION*

This Project Agreement is entered into among the Federal Energy Technology Center (FETC) of the Department of Energy of the United States of America, the New Energy and Industrial Technology Development Corporation (NEDO) of Japan, and the Research Council of Norway (NRC) (collectively the "Parties").

WHEREAS, in 1995 member countries of the International Energy Agency and the Organization for Economic Cooperation and Development created the Climate Technology Initiative (CTI);

WHEREAS, the CTI seeks to support the objectives of the United Nations Framework Convention on Climate Change by increasing the use of existing climate-friendly technologies and developing new and improved climate-friendly technologies through the promotion of international cooperation in research, development, deployment and information dissemination;

WHEREAS, an objective of CTI's Task Force 7 is to enhance international collaboration in research and development in greenhouse gas capture and disposal, including research on ocean sequestration of CO<sub>2</sub>; and

WHEREAS, the CTI's Task Force 7 invites the Parties to explore on an international collaborative basis the technical feasibility and environmental impact of CO<sub>2</sub> ocean sequestration, in order to advance current knowledge of the behavior of discharged CO<sub>2</sub> in the ocean;

NOW THEREFORE, the Parties agree as follows:

Article 1  
Objective of the Project

The objective of the international collaboration project on CO<sub>2</sub> ocean sequestration (the "Project") is to determine the technical feasibility of, and improve understanding of the environmental impacts of, CO<sub>2</sub> ocean sequestration in order to minimize the impacts associated with the eventual use of this technique to reduce greenhouse gas concentrations in the atmosphere.

Article 2  
Scope of Work

To advance current knowledge of the behavior of discharged CO<sub>2</sub> in the ocean, joint research shall be undertaken which mainly focuses on dissolution-type CO<sub>2</sub> discharge experiments conducted at an ocean site. In this joint research, a CO<sub>2</sub> injection system will be constructed and operated to observe near-field phenomena such as droplet plume dynamics and subsequent peeling and intrusion of enriched water. This joint research shall be conducted within the estimated cost of the Project as described in Article 9.

### Article 3 Work Program

The program of work for the Project (hereinafter the "Work Program") shall be as follows:

1. Selection of the most suitable site for ocean field experiments.
2. Determination of the discharge depth, rate, timing and duration of experiments.
3. Design of facilities for CO<sub>2</sub> storage, transport and discharge.
4. Selection of the items to be measured and monitored in experiments.
5. Preparation and testing of equipment for measurement and monitoring.
6. Construction of CO<sub>2</sub> storage, transport and discharge facilities.
7. Carrying out of ocean field experiments.
8. Analysis of data acquired during experiments.
9. Collation of overall results obtained in the field experiments.
10. Formulation of a proposal for the next phase of the Project.
11. Other activities as may be mutually agreed by the Parties in writing.

All Parties shall cooperate with one another to promote the Work Program.

### Article 4 Addition and Withdrawal of Project Participants

(1) Upon approval of the Steering Committee (described in Article 6), participation in the Project shall be open to other organizations which sign or accede to this Project Agreement, accept the rights and obligations of a Party, and make an appropriate contribution to defray the cost of the Project.

(2) In the event a Party wishes to withdraw from the Project for budgetary or other reasons, it may do so at the end of a fiscal year (as defined in Article 8) upon sixty (60) days' written notice to the other Parties.

### Article 5 Implementing Research Organizations

(1) Each Party may implement Project activities through an appropriate domestic research organization (hereinafter "Implementing Research Organization"). Alternatively, a Party may undertake Project activities itself.

(2) The Parties' designated Implementing Research Organizations are as follows:

For FETC:

Massachusetts Institute of Technology (United States of America)

For NEDO:

Research Institute of Innovative Technology for the Earth (Japan)

For NRC:

Norwegian Institute for Water Research (Norway)

(3) The Parties shall support their respective Implementing Research Organizations by providing annual funding to be used for implementing the Project, subject to Article 9.

(4) In order to establish work responsibility, details regarding treatment of intellectual property, and necessary policy and procedure for the Project, the Implementing Research Organizations shall conclude an annual joint research agreement for each fiscal year of the Project.

#### Article 6

##### Steering Committee

(1) A committee consisting of one representative of each Party (hereinafter "Steering Committee") shall be established to manage the overall direction and scope of the Project and to consider and approve the participation of other organizations in the Project.

(2) The Steering Committee shall be responsible for resolving any misunderstandings or problems related to this Project Agreement or the Project based on the principles of mutual benefit, equality, cooperation and trust.

(3) The Steering Committee shall hold its first meeting within one (1) month of the execution of this Project Agreement to establish duties, policies and procedures for implementing the Project. Following its first meeting, the Steering Committee shall meet approximately once a year at a place mutually agreed by all members.

#### Article 7

##### Technical Committee

(1) The Parties shall establish a Technical Committee consisting of up to three (3) representatives appointed by each Implementing Research Organization, to formulate the annual Work Program for each year of the Project, to supervise its technical aspects and execution, and to consult about treatment of intellectual property.

(2) The Technical Committee shall also be responsible for managing the budget for implementing the Work Program and coordinating any optional research studies which may be undertaken during the Project.

(3) The Technical Committee shall report to the Steering Committee at least twice a year regarding implementation of the annual Work Program for the Project.

(4) The specific functions of the Technical Committee shall be set forth in the annual joint research agreements among the Implementing Research Organizations.

#### Article 8

##### Project Fiscal Year

The Parties agree that the fiscal year of the Project shall extend from April 1st to March 31st of the following year.

Article 9  
Cost Contributions

The total estimated cost of the Project is Three Million Eight Hundred Thousand U.S. Dollars (U.S. \$3,800,000). Subject to the availability of appropriated funds and appropriate authorizations by their respective governments, the Parties agree to share the cost of the Project as follows:

**Agency**  
**Funding Level (U.S.\$)**  
**Percentage of Funding**

**FETC**  
\$850,000  
22.4%

**NEDO**  
\$2,600,000  
68.4%

**NRC**  
\$350,000  
9.2%

Article 10  
Treatment of Project Results

Basic policy regarding the use and protection of research data and intellectual property resulting from Project activities shall be determined through mutual discussion and agreement of the Parties. Specific details concerning the treatment of project results shall be included in the annual joint research agreements provided for under Article 5.

Article 11  
Waiver of Claims for Damages

In the event of any material damage or loss of life due to an accident or any reason other than willful misconduct or gross negligence during the implementation of the Project, no compensation shall be claimed by any Party against any other Party or against the Implementing Research Organizations.

Article 12  
Amendment of this Agreement

In the event the Steering Committee determines that it is necessary to amend this Project Agreement, it may be amended by written agreement of the Parties.

Article 13  
Mutual Trust and Cooperation

(1) Each Party shall endeavor, in the spirit of mutual trust, to resolve any difficulties or misunderstandings which might arise concerning the Project or this Project Agreement.

(2) Each Party shall conduct the collaboration under this Project Agreement in accordance with the applicable laws and regulations under which each Party operates.

(3) Any questions arising in connection with the interpretation or implementation of this Project Agreement or anything not specified herein shall be promptly discussed through mutual consultation among the Parties.

#### Article 14

##### Responsibility for and Use of Information

(1) The Parties support the widest possible dissemination of information generated by Project activities. Such information may be made available for public dissemination at the discretion of the Parties, subject to the need to protect proprietary information in accordance with Article 14(2).

(2) The Parties shall take all necessary measures as they may consider appropriate to protect proprietary information. For the purposes of this Article, proprietary information shall include information of a confidential nature such as trade secrets and know-how (for example, computer programs, design procedures and techniques, chemical composition of materials, or manufacturing methods, processes or treatments) which:

(i) is not generally known or publicly available from other sources;

(ii) has not previously be made available by the owner to others without obligation concerning its confidentiality; and

(iii) is not already in the possession of the recipient without obligation concerning its confidentiality.

It shall be the responsibility of each Party supplying proprietary information to identify the information as such and to ensure that it is marked "Proprietary Information".

(3) Information transmitted by one Party to another Party shall be accurate to the best knowledge and belief of the transmitting Party, but the transmitting Party does not warrant the suitability of the information transmitted for any particular use or application.

#### Article 15

##### Effective Date, Extension, and Termination

(1) This Project Agreement shall be effective from the date of its signing by all Parties through March 31, 2002, unless extended or terminated.

(2) By mutual written agreement, the Parties may extend this Project Agreement for additional periods.

(3) The Parties may by mutual written agreement terminate this Project Agreement at any time.

IN WITNESS WHEREOF, each Party has executed this Project Agreement on the date indicated, with each Party to retain one (1) fully executed copy.

Federal Energy Technology Center  
Department of Energy  
United States of America

Signature:

Name: Harvey M. Ness

Title: Director, Power and Environmental Systems

Date: December 4, 1997

New Energy and Industrial Technology  
Development Organization  
Japan

Signature:

Name: Hiroshi Mitsukawa

Title: Executive Director

Date: December 4, 1997

Research Council of Norway  
Norway

Signature:

Name: Eirik Normann

Title: Assistant Director

Date: December 4, 1997

## APPENDIX B: PUBLIC OUTREACH PROGRAM

As the implementing organization, the Pacific International Center for High Technology Research (PICHTR) developed and initiated an extensive public outreach program for the *Ocean Sequestration of Carbon Dioxide Field Experiment*. The outreach program has had several key purposes:

- Expand pre-consultation process to include environmental and community organizations, as well as other local stakeholders in order to provide an opportunity to give input into the experimental design.
- Work with stakeholders to keep them well informed and to listen to their concerns.
- Instill a sense the *Field Experiment* would be conducted with full public knowledge.
- Secure an understanding of the *Field Experiment's* importance to informed public policy decision-making.

The public outreach program consists of several phases. Those phases, and the objectives of each, are outlined below.

**Phase I: Gather Information and Prepare Outreach.** Develop a public outreach program for the *Ocean Sequestration of Carbon Dioxide Field Experiment*. Identify key contacts, including: NELHA tenants; citizen and native Hawaiian marine advocates; scientists and extension agents; West Hawai'i Fishery Council; private sector representatives; and elected officials.

**Phase II: Prepare NELHA Site Proposal.** Build understanding of the rationale for conducting the *Field Experiment* at the Natural Energy Laboratory of Hawai'i Authority's Ocean Research Corridor. Listen to and address concerns through mailing information packages to key contacts, telephone calls and one-on-one (or small group) meetings with decision-makers, media contacts, and project-related articles and opinions published in local newspapers and magazines. On August 6, 1999, a project presentation was made at a NELHA Tenants Association Meeting. A web site containing descriptive information concerning the *Field Experiment* and links to other relevant web sites was established ([www.co2experiment.org](http://www.co2experiment.org)). This web site has been updated several times in subsequent phases. The project web site includes an Email address for the public to submit comments. The project team has made great efforts to try and respond to all public inquiries. Email correspondence with the public has continued in subsequent phases.

**Phase III: NELHA Site Proposal and Review.** Continue building community involvement and initiate formal environmental scoping. Activities included presenting at a University of Hawai'i Sea Grant Extension Service's REEFTALK (September 14, 1999), showing a video of this presentation several times in November 1999 on a West Hawai'i public access cable channel. The project team also briefed the NELHA Board, held a public scoping meeting for the Environmental Assessment, and informed project leadership about concerns so that appropriate adjustments could be made in the *Field Experiment's* design.

**Phase IV: Prepare EA and (if necessary) apply for permits.** Foster public understanding and ensure plans for the *Field Experiment* are adjusted as needed. On March 1, 2000, a presentation was given to the Hawaiian Islands Humpback Whale National Marine Sanctuary Advisory Council. Email correspondence between the project team and local stakeholders continued throughout this and other phases.

**Phase V: Final activities prior to conducting *Field Experiment*.** The next phase in the extensive public outreach effort is in the time leading up to the actual conducting of the *Field Experiment*. Planned activities include: (i) preparing and circulating a press release prior to initiation of the *Field Experiment* and (ii) continuing background briefings with media contacts at West Hawaii Today, Hawaii Tribune-Herald, Honolulu Star-Bulletin, and the Honolulu Advertiser.



**Phase VI: Experiment Phase and Post-Experiment Activity.** Provide the public with current and accurate information on the final preparation for and conducting of the *Field Experiment*. Results of the *Field Experiment* would be published in the technical literature available to the public. In addition, if the project web site remains activated for a sufficient time after the completion of the *Field Experiment*, data and results may be posted and thus become available online. It must be realized, however, that for technical reasons there usually is a substantial delay between the collection of raw field data and their availability as calibrated or processed information. An even longer delay should be anticipated in the case of peer-reviewed technical literature. The presence of observers during the execution of the *Field Experiment* would pose logistical and safety problems. While observers that are not directly affiliated with the project could be admitted onboard the research vessels, a strict protocol would have to be enforced to ensure everyone's safety and to avoid interference with ongoing experimental and monitoring activities. Such a protocol would naturally restrict the number of people who could serve as observers.

***APPENDIX C: DRAFT EXPERIMENTAL PLAN FOR THE OCEAN  
SEQUESTRATION OF CO<sub>2</sub> FIELD EXPERIMENT***

*DRAFT*

**EXPERIMENTAL PLAN  
FOR THE  
OCEAN SEQUESTRATION OF CO<sub>2</sub>  
*FIELD EXPERIMENT***

**THE PACIFIC INTERNATIONAL CENTER  
FOR HIGH TECHNOLOGY RESEARCH  
HONOLULU, HAWAII**

**MAY 2001**

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## 1.0 INTRODUCTION

### 1.1 BACKGROUND

Through controlled release of fixed amounts of liquid CO<sub>2</sub> totaling 20 - 40 metric tons (22-44 English, or short, tons), the *Field Experiment* would develop information on (1) physical and chemical changes induced in seawater by the release of liquid CO<sub>2</sub> and (2) effects of release rates and nozzle designs on the physical dynamics of a CO<sub>2</sub> cloud of droplets. In addition, sampling of biota and a study of naturally occurring bacteria populations in the immediate vicinity of the discharge nozzle would be conducted, and the results would be compared with background information for preliminary investigations of biological effects caused by CO<sub>2</sub> injection. Data collected during the *Field Experiment* would allow scientists to test and refine the theoretical models they use to predict the behavior of liquid CO<sub>2</sub> released into the ocean at moderate depths (2,300-4,900 feet; about 700-1,500 meters).

The *Field Experiment* would consist of a series of tests. Each test would be used to observe and evaluate the behavior of a specific nozzle design while operating under varying CO<sub>2</sub> discharge rates or physical conditions. The equipment needed to conduct the tests would be mounted on, and deployed from, vessels chartered for that purpose. One vessel would carry the equipment used to release the liquid CO<sub>2</sub>. A discharge platform would be carried on the deck of the ship until it is in position for deployment. A test nozzle would be fitted to the end of an outlet pipe on the platform, and the platform's inlet pipe would be connected, using a short length of flexible hose, to one end of coiled tubing through which liquid CO<sub>2</sub> would be pumped from the vessel. The platform would then be lowered to the bottom at an estimated water depth of 2,600 feet. The vessel used to deploy the discharge platform and flexible tubing would have good positioning capabilities. That is, the vessel would contain the navigational and mechanical equipment needed to remain in a fixed position without using an anchor. Other vessel(s) would transport remotely operated vehicles (ROVs) and/or submersibles that would be used to collect data during the *Field Experiment*. Instrumentation used for data collection would include ocean current meters, pH meters, video cameras, and other oceanographic tools. Moored systems would be deployed to obtain continuous records of oceanographic variables at fixed locations, while the ROV system would be used to follow the discharge plume down current.

### 1.2 PURPOSE OF THIS DOCUMENT

This document details the experimental plan that would be followed in conducting the experiment. It complements the information that is contained in the Environmental Assessment that the U.S. Department of Energy has completed for the project.<sup>1</sup> It includes:

- A list of the experimental objectives.
- An overview of the kinds of measurement platforms and instruments that will be used.
- A detailed description of the experimental activities.
- A summary of the actions that would be taken to modify or suspend the planned activities in the event that real-time monitoring of the results indicates that the CO<sub>2</sub> is behaving in unanticipated ways that have the potential to significantly affect the surrounding environment.

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<sup>1</sup> A Finding of No Significant Impact was released by DOE on May 4, 2001 based on this Environmental Assessment.

## 2.0 EXPERIMENTAL OBJECTIVES

The overall objective of the *Ocean Sequestration of CO<sub>2</sub> Field Experiment* is to provide data needed to verify scientific principles and to test, validate, and refine existing computer and laboratory models concerning the behavior of liquid CO<sub>2</sub> released into the ocean at moderate depths (2,300-4,900 feet; about 700-1,500 meters). More specific objectives of the *Field Experiment* are to:

- Investigate CO<sub>2</sub> droplet cloud dynamics;
- Examine pH in the plume and on its margins;
- Clarify effects that hydrates might have on droplet dissolution;
- Trace the evolution of CO<sub>2</sub>-enriched seawater resulting from CO<sub>2</sub> dissolution;
- Assess potential impacts on bacterial biomass, production, and growth efficiency associated with induced changes in seawater pH in the vicinity of the release; and
- Examine the effect of a range of CO<sub>2</sub> injection velocities and injector configurations (*e.g.*, orifice size) on the performance of the system and on physio-chemical effects.

## 3.0 MEASUREMENT PLATFORMS & INSTRUMENTS

### 3.1 OVERVIEW

Figure 3-1 shows the various platforms to be used for experimental measurements. Those platforms, the kinds of instruments that would be mounted on each, and the sorts of measurements that would be made by each are briefly described below.

Several different measurement and sampling platforms will be used. These include:

- A remotely operated vehicle (ROV), referred to as an RTV (remotely operated television), will observe the behavior of droplets near the nozzle. A separate ROV or manned submersible will at other times conduct surveys of the water column and collect samples from the water column and the bottom within about 100 meters of the discharge platform.
- Small instrument packages will be deployed from the research vessels on fixed moorings and the discharge platform and will collect data from those locations.
- The research vessels will lower instruments to take conductivity-temperature-depth (CTD) measurements at varying distances from the discharge nozzle.

Instruments mounted on (or deployed from) these platforms will be used to collect a wide range of data. Collectively, the scientific team will be sampling the following:

- pH (using probes mounted on the RTV and ROV or submersible, CTD instruments cast from the research vessels, and instruments moored temporarily on the bottom).
- Carbon chemistry (including pH; measured in samples collected by the ROV or submersible and CTD bottles brought onboard ship).
- Microbiology (bacterial production, respiration and community structure; measured in samples collected by the ROV or submersible and CTD bottles brought onboard ship).
- Noise (measured with a hydrophone).
- Hydrography (temperature, salinity and density measured using CTDs and instruments mounted on the ROV or submersible).
- Ambient current speed and direction using an Acoustic Doppler Current Profiler (ADCP) deployed from a research vessel and an Acoustic Doppler Velocity meter (ADV) mounted on the ROV or submersible.
- Benthic biology (from samples collected by the ROV or submersible).
- Tracer dye concentration measured with a fluorometer that will be connected to the ROV or submersible or moored in situ downstream from the CO<sub>2</sub> release.
- Video observations using cameras mounted on both the RTV and ROV or submersible.

### 3.2 DETAILED DESCRIPTION OF INSTRUMENTATION

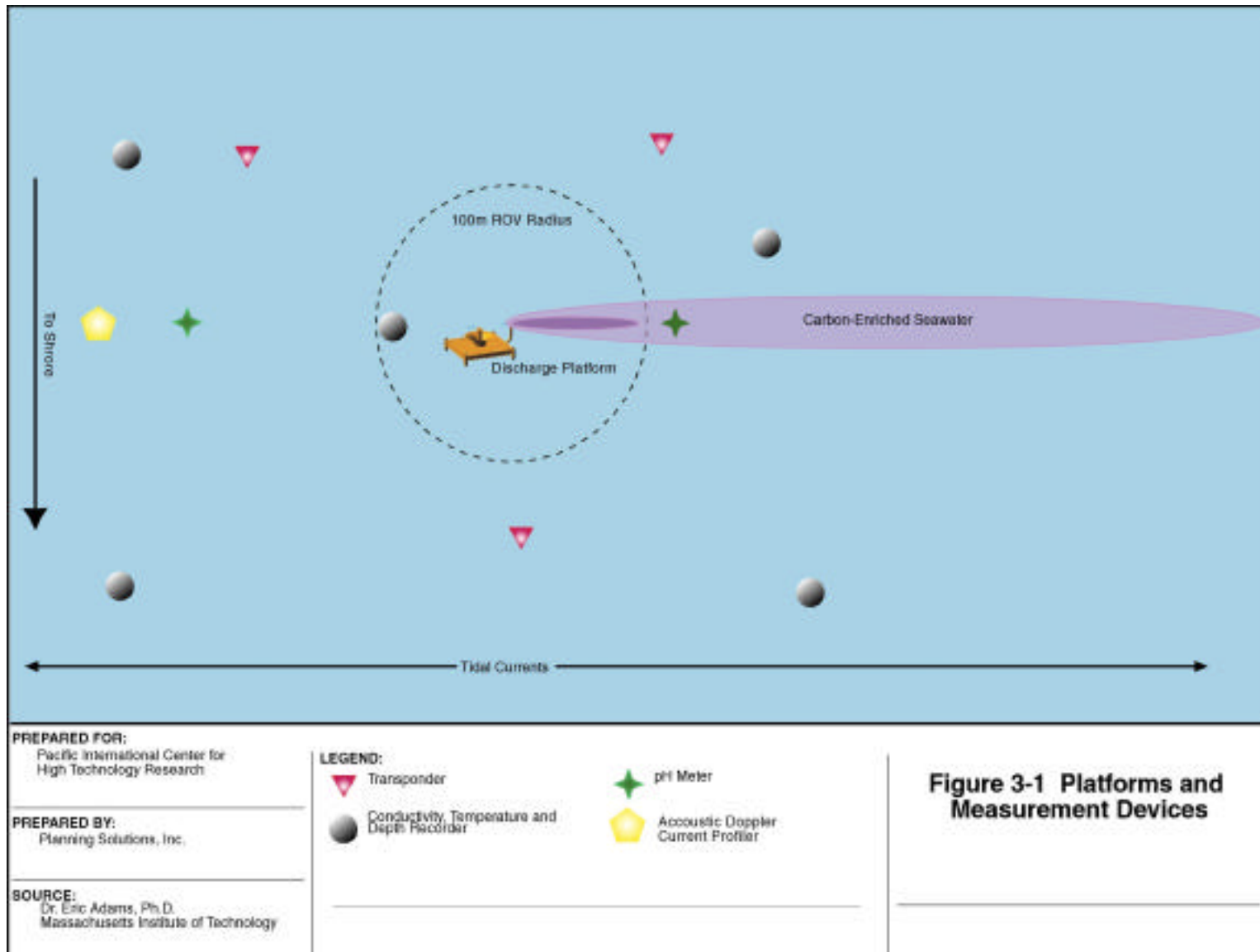
Table 3-1 summarizes the instruments and measurements associated with each of the platforms that would be used to conduct the experiment.

## MEASUREMENT PLATFORMS &amp; INSTRUMENTS

Table 3-1 Summary of Instrumentation By Platform

<i>Platform</i>	<i>Instruments/Measurements</i>
<b>RTV (Japanese ROV)</b>	<p><b>Video Camera/Recorder.</b> Observations of CO<sub>2</sub> droplets. Real-time data would be transmitted from the RTV to the research vessel via cable. Data would be recorded for future analysis.</p> <p><b>pH Meters.</b> pH meters with real-time data transmission to the research vessel via the cable umbilical line.</p> <p><b>Video Camera/Recorder.</b> Observations of biota in water column and on the seafloor to observe reaction. Because reactions are expected to be small and occur over a period of time, most analysis of these data would be done after the experiment is completed.</p>
<b>ROV or Submersible</b>	<p><b>pH Meters.</b> pH meters with real-time data transmission to the research vessel.</p> <p><b>Geological Samplers.</b> Sampling devices will collect sediment and rock samples from the bottom for later laboratory analysis related to benthic biology and microbiology. Microbiological data will allow estimates of bacterial production, respiration, and community structure.</p> <p><b>Video Camera/Recorder.</b> Observations of CO<sub>2</sub> droplets. Real-time data would be transmitted from the ROV to the research vessel via cable or be observed and recorded on a submersible. Data would be recorded for future analysis.</p> <p><b>Video Camera/Recorder.</b> Observations of benthos to observe reactions of fauna. Because reactions are expected to be small and occur over a period of time, most analysis of these data would be done after the experiment is completed.</p> <p><b>Fluorometer.</b> A fluorometer attached to the ROV or submersible would be used to measure fluorescent dye concentrations in the discharge. This would enhance the ability to track the plume.</p> <p><b>Conductivity, Temperature, Depth Sensor.</b> CTD sensors would be included in the sensor package on the ROV or submersible to characterize the seawater bodies through which the mobile survey system travels.</p> <p><b>Acoustic Doppler Velocity Meter.</b> This instrument would measure relative current speed while mounted on the mobile survey system.</p> <p><b>Water Column Samples.</b> Samples would be collected using the CTD collection bottle for on board analysis of carbon chemistry and microbiological processes.</p>
<b>Fixed Moorings</b>	<p><b>Hydrophone.</b> This instrument would measure noise levels near the discharge platform. Data would be transmitted to the research vessels periodically through a low-speed acoustic modem. Could be deployed from the research ship also.</p> <p><b>pH Meters.</b> pH levels – data are stored for analysis after the mooring is recovered.</p> <p><b>Acoustic Doppler Current Profiler (ADCP).</b> The ADCP would provide real-time data concerning current velocity and direction by depth throughout the water column through an acoustic modem to the research vessels.</p>
<b>Research Vessel</b>	<p><b>Conductivity, Temperature, Depth Sensors.</b> CTD sensors would be deployed from the research vessel and on fixed moorings to characterize the seawater bodies throughout the water column below the ship. Water samples would also be collected for onboard analysis.</p>





## 4.0 DESCRIPTION OF EXPERIMENTAL ACTIVITIES

### 4.1 GENERAL

Table 4-1 summarizes the most important characteristics of the planned tests. It must be stressed that the tasks and durations that are shown are tentative. As is true of all experimental activities, the work plan must remain flexible to allow the investigators to respond to such things as weather patterns, sea states, instrument and shipboard equipment malfunctions, unexpected findings, etc. In particular, the number of tests might be increased beyond the number described in the following sections, based on the constraints of time and resources. However, the maximum flow rates and daily discharge quantities would not be increased, and the total amount of liquid CO<sub>2</sub> discharged would not exceed 40 metric tons. The following section describes the manner in which the experiment would be conducted.

#### 4.1.1 PLANNED EQUIPMENT

The equipment needed to conduct the *Field Experiment* would be mounted on, and deployed from, ocean-going vessels chartered for the purpose. There would be a vessel used to deploy the CO<sub>2</sub> release system and one or two vessels used to monitor the results of the release. These are described in more detail in the following sections.

##### 4.1.1.1 Carbon Dioxide Delivery Vessel

One vessel would carry the equipment used to release the liquid CO<sub>2</sub>. This vessel would have good positioning capabilities, which means that it would have navigational and mechanical equipment needed to remain in a fixed position without use of an anchor. The equipment mounted on the vessel would consist of the following:

- A standard refrigerated CO<sub>2</sub> storage tank system of the type widely used by food and beverage companies and hospitals. The deck-mounted tank would keep the CO<sub>2</sub> at a pressure of 20 to 22 bar and -4° F (-20° C).
- A pump, metering system, and high-pressure hose capable of delivering the liquid CO<sub>2</sub> from the storage tank into coiled tubing, through which the CO<sub>2</sub> would be transported to the discharge platform and nozzle on the seafloor.
- A reel holding approximately 3,940 feet (1,200 meters) of 1.5- to 2-inch (3.81 to 5.08 centimeter) outside-diameter coiled tubing, a control cabin with hydraulic power pack, and a deck-mounted container housing controls for the other equipment.

A discharge platform would be carried on the deck of the ship. When the vessel is in position for deployment, a test nozzle would be fitted to the end of the outlet pipe, and the inlet pipe would be connected to the end of the coiled tubing. The platform would then be lowered to the bottom at an estimated water depth of 2,600 – 3,300 feet (800 – 1,000 meters). The platform would be about six or seven feet wide by thirteen feet long and would weigh approximately 11,000 pounds. The discharge platform would consist of the following:

- A flat, steel structure that would provide sufficient tension to the tubing during deployment to minimize drifting due to currents.
- A vertical steel pipe connected to the CO<sub>2</sub> supply tubing by a short, flexible hose secured by chains. The connection would also include a swivel joint to minimize torsion forces in the tubing.
- A trumpet-shaped guide to prevent kinking in the CO<sub>2</sub> supply line.
- Four pointed, steel legs to minimize horizontal movements on the hard seabed, which can have a slope of as much as 30 degrees.

**Table 4-1 Basic *Field Experiment* Matrix**

Duration of Each Test Release (approximate)	Two Hours
CO <sub>2</sub> Flow Rates	1.6 to 9.5 gallons per minute (0.1 to 0.6 kg/s)
Number of Nozzle Designs Tested	2
Ambient Conditions	Conduct tests at range of current speeds, if possible
Baseline Number of Test Releases	9 <sup>2</sup>
Total Amount of CO <sub>2</sub> Released	Approximately 5,200 – 10,400 gallons (20 – 40 metric tons)
Source: Pacific International Center for High Technology Research (PICHTR)	

- A discharge pipe to which the test nozzle would be attached; the discharge pipe would extend outward and upward from the side of the platform.
- Anti-backflow devices, such as a check valve, to prevent seawater from entering the pipe and causing hydrate blockages.

The platform may also be equipped with electric heaters to 'melt' any hydrates that form, transponders, tracer dye injectors, and other small pieces of scientific equipment.

#### **4.1.1.2 Other Support Vessels and Equipment**

Other vessels would be used to support the *Field Experiment*. These would include one or two mother ships to deploy the remotely operated vehicle (ROV) or submersible and the remotely operated television (RTV) systems that would be used to collect data during experimental tests. In addition, a small boat might be chartered to carry scientists and samples between the research vessels and the shore if this is logistically practical. As discussed elsewhere, small chemical and physical sensors, as well as ROV transponders, would be placed temporarily on the seafloor during the *Field Experiment*.

#### **4.1.2 PROPOSED TEST SEQUENCE: GENERAL**

The *Field Experiment* would consist of a series of test sequences. Each test is designed to observe and evaluate the behavior of a specific nozzle design while operating under a defined release rate and known physical conditions. It is expected that two different nozzle designs would be tested, and an effort would be made to conduct the releases over a range of current speeds. Altogether, approximately 5,200 gallons (20 metric tons) of CO<sub>2</sub> would be released over the course of the initially planned tests.

Tests would only be conducted when weather and sea conditions allow vessels to maintain their positions within a designated area. Based on equipment requirements, the preferred surface current for conducting tests would be 2 knots (about 1 meter per second) or less.

The vessel deploying the platform would maintain station while the coiled tubing is extended for a single experimental test series. In general, this means that the vessel would be stationary above the platform for periods ranging from 8 hours to 3 days.

<sup>2</sup> More testing might be conducted, based on the results of the initial tests as well as cost and logistical considerations. The maximum release rate for CO<sub>2</sub> would be limited to 0.6 kg/s and the total amount of CO<sub>2</sub> to be released would be limited to 40 metric tons.

#### 4.1.2.1 Deployment

Before the discharge platform is lowered from the ship, one of the specially designed nozzles would be attached to the end of the CO<sub>2</sub> discharge pipe. Each nozzle would likely consist of a vertical riser (pipe) about 8 inches (20 centimeters) in diameter that ends in a blind flange with 10 to 60 small holes for release ports.

When prepared for deployment, the platform and attached coiled tubing would be slowly lowered into the water. The weight of the platform would result in a virtually vertical descent of the assembly.

While deploying the platform, the ship would maintain station within a radius of approximately 80 feet (25 meters) over the platform's intended resting-place on the bottom. After the platform reaches the bottom, additional tubing would be deployed until approximately 650 to 1,000 feet (200 to 300 meters) of tubing would be laid on the seafloor. Laying out this additional tubing would provide an unobstructed space immediately above the discharge platform so that survey systems, such as the RTV, ROV, and submersible, would have a clear view of the CO<sub>2</sub> plume. The separation is also needed to prevent possible entanglements between the ROV cables and CTD cables that connect these survey systems to the research vessel and the CO<sub>2</sub> supply pipeline.

The platform would likely be raised from the seafloor at least once during the course of the experiment to change the discharge nozzle, to perform maintenance on the nozzle and/or discharge platform instrumentation, or to correct any operational problems. No more than 5 deployments of the discharge platform are anticipated; this is half the maximum of 10 that were used in the Environmental Assessment for impact prediction.

#### 4.1.2.2 Carbon Dioxide Release

Following proper placement of the discharge platform on the bottom, the CO<sub>2</sub> release through the nozzle being tested would begin. The design of each nozzle would generate a unique assemblage of CO<sub>2</sub> droplets at each release rate. As indicated in Table 4-1, the CO<sub>2</sub> would be released from the nozzle at maximum flow rates of 9.5 gallons per minute (0.6 kilograms per second).

Following each release, two distinct regimes of CO<sub>2</sub> behavior are expected. The first regime would consist of rising droplets of liquid CO<sub>2</sub>, with droplets possibly covered with films of hydrated CO<sub>2</sub>. The release rate and the design of the nozzle would largely control both the size and shape of the droplets and the extent of hydrate formation.

The second regime would result as the buoyant, rising droplets dissolve in seawater. The droplets would gradually dissolve because the natural concentration of inorganic carbon in ambient seawater is orders of magnitude below the solubility limit for liquid CO<sub>2</sub>. At the release rates planned for the *Field Experiment*, the vertical rise of the liquid CO<sub>2</sub> droplets would cease within 1,000 feet (~300 meters) from the nozzle. The dynamics of the ascending droplets would be complex, with some seawater being entrained upward by the momentum of the rising droplets. CO<sub>2</sub>-enriched water along the edges of the rising plume would sink as dissolved concentrations of carbon increase. This relatively dense, carbon-rich seawater would stop sinking when sufficient mixing with lighter ambient seawater would bring the mixture to a neutrally buoyant equilibrium. Then, the carbon-rich water would drift with the current while being diluted further by turbulence. Examination of this complex, near-field behavior is the primary objective of the *Field Experiment*.

#### 4.1.2.3 Monitoring Methods

During each test, staff on the vessel deploying the platform would: operate and monitor the CO<sub>2</sub> pump system and nozzle flow rate; maintain the vessel's position; and interface with project administrators and the ships from which the ROVs or submersible would operate.

The crew and staff of the vessel or vessels deploying the survey systems would: make ocean measurements; control and monitor the system locations; provide feedback concerning the behavior of the

## DESCRIPTION OF EXPERIMENTAL ACTIVITIES

release and the condition of the discharge platform; visually monitor the behavior of visible organisms near the test release; and conduct related tests and measurements. Sampling bottles would be deployed and retrieved from the research vessels to collect water and sediment for chemical and biological (bacterial) analysis. Conductivity, temperature, and depth (CTD) measurements from the research vessel would supplement the data obtained from small sensors moored temporarily on the bottom and from the ROVs or submersible.

The CO<sub>2</sub> droplets would be visible and tracked directly using the video equipment mounted on the RTV and the ROV or submersible. Dissolved carbon in the carbon-rich water plume would not be visible and would need to be monitored indirectly. Since CO<sub>2</sub> would increase acidity (lower pH) of the seawater as it dissolves, the plume would be distinguished from normal seawater by measuring the pH. This would be done continuously using instruments mounted on the RTV and ROV or submersible. These vehicles would follow a zigzag course through the droplet cloud and plume of carbon-enriched seawater. Scientists would use real-time measurements of pH to help determine the lateral and vertical edges of the plume for purposes of guiding the ROV or submersible on its survey path. Non-toxic tracers, such as fluorescent dyes, would also probably be released with the CO<sub>2</sub> to facilitate monitoring.

The instruments described in Table 3-1 would be used to monitor ambient conditions and perturbations resulting from the experiment itself. Instruments on the RTV and ROV or submersible (e.g., a solid state pH sensor, a more traditional glass electrode pH probe, a fluorometer, an Acoustic Doppler Velocity meter (ADV), and video camera) would monitor the plume continuously during releases at distances up to about 100 meters from the release point. Beyond this distance, the scientists believe that the plume would be difficult or impossible to follow consistently. These measurements would be available in real time and would be used to help guide the survey path followed. These surveys will focus on the near field, where the pH would be lowest. The moored instruments would be approximately 200 meters from the discharge.<sup>3</sup> Because of this distance, and the fact that the moored instruments are fixed in space while the plume will meander, these fixed instruments may or may not be in the center of the plume and record the highest concentration of plume constituents.

Data collected during each test would be used to produce detailed maps of the parameters under scientific investigation (e.g., pH, temperature, and salinity) and of the ocean current fields. The mobile video systems would provide flow images of the CO<sub>2</sub> droplet evolution over time. The ADV would obtain point measurements of fluid velocities for use in evaluating turbulence within the discharge plume. Small transponders on the seafloor would be used to track the underwater position of the mobile systems.

Data obtained on CO<sub>2</sub> droplet cloud dynamics, effects of hydrate films on droplet dissolution, and three-dimensional mapping of the dispersing, CO<sub>2</sub>-enriched seawater would be used to assess the physical and chemical effects of CO<sub>2</sub> sequestration in ocean water.

To assess potential impacts of CO<sub>2</sub> sequestration on environmental health, variations in bacterial biomass, productivity, and growth efficiency would be determined and compared to conditions in the ambient water column. Measurement of nutrients (dissolved and particulate organic carbon and organic nitrogen) would be conducted for corollary analysis. These measurements would identify changes in substrate availability that could alter bacterial activity during injection of CO<sub>2</sub>. The analysis of bacterial cycling rates would be combined with an analysis of the variation in bacterial genetic diversity to interpret stresses that might arise from pH changes. This information would provide a better understanding of the effect of water column acidification on the base of marine food chains. These data would also be collected to confirm that the experiment protects overall water quality.

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<sup>3</sup> The moored instruments need to be well separated from the discharge platform to insure that the ROV or submersible will not strike them. Because of this, they are most effective at measuring ambient background levels rather than at recording near field perturbations caused by the CO<sub>2</sub> release.

#### 4.1.3 POST TEST/SITE CLEAN-UP

Because of the deployment method planned, the discharge platform, nozzle, and tubing would be removed from the seabed. The small instrument packages and transponders that would be deployed around the test area would also be retrieved.

### 4.2 DETAILED DEPLOYMENT, RELEASE, AND MONITORING SCENARIO

Table 4-2 depicts the most current plan for conducting the *Field Experiment*. Table 4-3 lists the typical activities that would take place during a normal day during the *Field Experiment*. General descriptions of these activities and their sequencing in the plan are provided below.

#### 4.2.1 SET-UP AND PACK-UP: MOORED SENSOR DEPLOYMENT AND RETRIEVAL

The first day that the research vessels are on station (Day 1 on Table 4-2) will be spent deploying the CO<sub>2</sub>-release system, collecting baseline data, and deploying the moored sensors. Video coverage of the area where the discharge platform will be deployed will be made to ensure that the selected site is free of obstacles and to collect a baseline video record of the site. Pre-survey sediment cores would be collected also. Depending on ship schedules and other logistical concerns, much of the pre-survey baseline data collection could be completed on an earlier, separate expedition to the site.

The moorings would consist of concrete or iron anchors connected by acoustic release devices to the instruments. These moored sensors include:

- The Acoustic Doppler Current Profiler (ADCP) that will be used to monitor ambient current speed and direction throughout the experiment.
- Fixed pH sensors that will be located around the experiment site.
- At least one hydrophone that will be used to measure noise from the experiment. It would be moored or deployed from the research ship.
- At least three acoustic transponders. When the transponders receive the proper acoustic codes from the ship, they emit short, distinctive acoustic signals that can be received by instruments on the research vessels and on the RTV/ROV/submersible. Equipment on the latter would allow scientists to fix the positions of the ships and the deployed instrument systems.

The moored sensors would be recovered on the final day of the experiment (tentatively Day 11). This would be done by raising them to the surface and lifting them onto the decks of the research vessels. Once the recovery is complete, the vessels would depart the area for their homeports or their next assignment. If possible, the submersible or RTV will collect video coverage of the seafloor locations of the moorings and discharge platform to permit assessment of the impacts made by the deployed seafloor operations.

#### 4.2.2 PRE-RELEASE OBSERVATIONS FOR DEPLOYMENT 1: LARGE NOZZLE OPENINGS (EXP 1)

Once all the necessary systems are in place, the RTV would follow. It would be used to confirm that the platform is stable and to conduct a visual survey of the area, including the other sensors that were lowered previously and the seafloor where the tubing is deployed. During this same period, the entire set of moored sensors would be exercised to establish that they are working properly. Readings on the moored pH sensors would be cross-checked against measurements made by instruments on the RTV to insure accuracy. Finally, the CO<sub>2</sub> would be turned on at a very small flow rate and the RTV would observe the rise of individual (or small collections of) droplets. The research vessels would also make CTD casts to collect physio-chemical water quality data. This last activity is identified as “Exp 1” in the table and may take up to eight hours.

## DESCRIPTION OF EXPERIMENTAL ACTIVITIES

**Table Error! No text of specified style in document.-1 Tentative Plan for the *Field Experiment***

Day	Platform	Exp	Nozzle Size	Mass rate (kg/s)	Measurement Tasks	Number of Releases [2]	Duration RTV/ Sub Work (hr)	Mass Released (T)
[1]			[7]				[3]	
1	Submersible		large		Deploy large diameter nozzle assembly w/ dye system			0
					i) Deploy amphipod cages, transponders;			
					ii) Check out Nozzle Assembly			
					iii) Collect baseline sediment cores			
2	RTV	1,2	large	0.1	i) Observe plume Near-field;	2	8	1.44
					ii) Dual pH-dye measurement			
					iii) Observe individual droplet ascent [4]			
3	Submersible	2	large	0.1	i) Video image of plume and sediment	2	8	1.44
					ii) Plume survey (pH plus water samples)			
					iii) Darkfield camera observations			
					iv) Towed cages			
					v) Sediment cores (after CO <sub>2</sub> stopped)			
4	RTV	3	large	0.6	Same as Day 2, but no measure of droplet ascent and only one survey	1	4	4.32
5	Submersible	3	large	0.6	i) Video image of plume and sediment	1	7	4.32
					ii) Plume survey (pH plus water samples)			
					iii) Darkfield camera observations			
					iv) Towed cages			
					v) Sediment cores (after CO <sub>2</sub> stopped)			
					vi) Monitoring (hours 3-5 after release)			
6	Submersible	3 cont	large	0.6	i) Video image of plume and sediment	1	7	4.32
					ii) Plume survey (pH plus water samples)			
					iii) Darkfield camera observations			
					iv) Towed cages			
					v) Sediment cores (after CO <sub>2</sub> stopped)			
					vi) Monitoring (hours 3-5 after release)			

Day	Platform	Exp	Nozzle Size	Mass rate (kg/s)	Measurement Tasks	Number of Releases [2]	Duration RTV/ Sub Work (hr)	Mass Released (T)
7					i) Deploy small diameter nozzle assembly w/ dye			7
					ii) Restock CO <sub>2</sub> (if necessary)			
8	RTV	4	small	0.25	Same as Day 2, but no measure of droplet ascent and only one survey	1	4	1.8
9	Submersible	4	small	0.25	Same as Day 3 except only one survey	1	4	1.8
10	Submersible				Sediment cores			
11[5]	Submersible				Sediment cores; pack-up		8	
							<b>Total[6]</b>	<b>19.44</b>

## Assumptions:

[1] All work with RTV/Submersible performed during daylight (limit of 8-10 hours on bottom). CTD/profiles/water column samples collected at night

[2] Each survey takes two hours (1 to establish steady flow; 1 to survey)

[3] RTV surveys could be conducted back-to-back; two hour interval between Submersible plume surveys to allow plume to flush (CO<sub>2</sub> is turned off).

Between Submersible plume surveys, Submersible can collect sediment cores, ambient water samples, harvest scavenged animals, etc.

[4] Individual droplet released from accumulator supplied by bleeding small quantity of CO<sub>2</sub> during Exp. 2

[5] Elapsed time on site is 11 days, including one day of contingency/nozzle re-deployment, and one day for monitoring

[6] Total CO<sub>2</sub> usage is about 20 tonnes, which may require having up to 30 tonnes on hand

[7] "Large" is designed to give mono or poly dispersed droplets and "small" is designed to give atomization (at low mass flow)



**Table 4-3 Typical Daily Survey Schedule**

Time	Activity
0700	Begin submersible Deployment
0800	Reach bottom; turn on CO <sub>2</sub> ; begin to collect scavenged animals; controlled exposure experiments
0900	Begin first water column survey
1000	End first water column survey; turn off CO <sub>2</sub> ; begin bottom coring
1100	End coring; begin to collect new scavenged animals; look for biological impact
1200	Turn on CO <sub>2</sub> ; crew break; controlled exposure experiments
1300	Begin second water column survey
1400	End second water column survey; turn off CO <sub>2</sub> ; begin bottom coring; look for biological impact
1500	End coring; begin ascent
1600	Reach surface; begin debriefing
1700	Begin dinner
1800	Scientist's analysis of day's survey; planning for tomorrow's survey
2100	End of analysis/planning
2200	Scientists return to berths
	At night: CTDs conducted; water and sediment cores analyzed

#### 4.2.3 LOW FLOW-RATE TEST FOR DEPLOYMENT 1: LARGE NOZZLE OPENINGS (EXP 2)

This test series, which would be made using a nozzle assembly having orifices with a diameter of 0.4 centimeters, would extend over the Days 2 and 3. All of the tests during this period would involve flow rates of 0.1 kilogram per second (1.6 gallon per minute). Approximately 1.44 metric tons of liquid CO<sub>2</sub> would be used. The low flow-rate tests are scheduled first to allow the scientists to check and improve on the experimental protocol as they learn from successive 2-hour releases.

Observations of the initial 2-hour release would be made using instruments on the RTV, which would remain in the water following completion of its baseline observations. It would observe the entire cloud of rising droplets, look for possible reactions on the part of marine biota, and take pH measurements of the carbon-enriched plume. Following completion of the release test, the mother ship would recover the RTV and prepare to launch either the ROV or the manned submersible. During this interim period, when all of the ship-launched sensors are out of the water, the research vessels will try to take vertical profiles of the plume with a CTD; this would give a continuous vertical distribution of pH.

The next set of measurements and releases would be made using sensors on the ROV or manned submersible. These would measure pH, collect water samples for subsequent analysis, collect samples of sediment from the bottom for laboratory analysis, and perform other tests not possible using the RTV. Most of the sampling would be done within the lowest 100 meters of the water column.

The extremely low density of organisms expected at the depth at which the experiment would be conducted makes it difficult to monitor biological effects on a real-time basis using only video observations of naturally occurring fauna. Because of this, the experimental protocol also calls for the use of test organisms carried in a basket on the outside of the ROV or submersible to monitor for deleterious effects. This would entail the following:

- Baited scavenger traps would be placed on the seafloor in the study area the day before each experiment. These traps would catch amphipods, decapod shrimp, teleost fishes, and other opportunistic scavenger feeders. Most of these organisms are sufficiently sensitive to environmental change to be used to monitor for the kinds of water quality changes that could result from the *Field Experiment*.

## DESCRIPTION OF EXPERIMENTAL ACTIVITIES

- When the ROV or submersible is deployed for a test, it would descend to the bottom and recover two of the traps. It would place one trap upstream from the nozzle as a control and place the other trap in its equipment rack and carry it about while it is carrying out its other monitoring tasks. The trap would be in a position where it could be observed in real-time using a video camera. A pH meter would be placed on the ROV or submersible close to the trap so that it would provide representative measurements of that parameter.
- During the experiment, a biologist would be present for the initial release and the first high-flow release of CO<sub>2</sub>. During those dives, time would be allocated to observe organisms that the plume encounters during and after the release. A biologist would observe the organisms in the trap on the seafloor as well as other organisms that may be visible in the environment. If the organisms within the trap are killed by exposure to the CO<sub>2</sub> plume, adjustments would be made as discussed in Section 4.3 of this plan.

This procedure will place the trapped organisms in the most strongly affected waters for an extended time. Because the organisms will receive a greater dose of CO<sub>2</sub> than free organisms in the environment, we expect them to be a sensitive indicator of possible temporary environmental harm. They may also be made more vulnerable to CO<sub>2</sub> exposure by the stress of capture and manipulation.

Subsequent series of tests would be made over the remainder of Experiment 2. Periods of release would be interspersed with periods when all of the observation vehicles (RTV, ROV/manned submersible) are out of the water. These interim periods would also provide time to make CTD casts, to repair equipment that is not operating properly, to adjust operational plans, taking advantage of information and insights that have been obtained during the previous tests, and to rest the ship crews and scientists.

#### 4.2.4 HIGH FLOW-RATE TEST FOR DEPLOYMENT 1: LARGE NOZZLE (EXP 3)

This test series (Experiment 3) would be conducted using the same nozzle assembly as the previous test series. It would extend over Days 4 - 6. All of the tests during this period would involve flow rates of 0.6 kilogram per second (approximately 9.5 gallon per minute). A total of about 13 metric tons of liquid CO<sub>2</sub> would be used during these test releases.

As with the low-flow discharge tests, observations of the initial 2-hour release would be made using the high-resolution video camera and pH measuring devices on the RTV. Scientists would use the camera to observe the entire cloud of rising droplets and to look for possible reactions on the part of marine biota. They would also take pH measurements of the carbon-enriched plume. Following completion of the first release test, the mother ship(s) would recover the RTV and prepare to launch either the ROV or the manned submersible. During this overnight interim period, when all of the ship-launched sensors are out of the water, the research vessels will try to take vertical profiles of the plume with a CTD; this would give a continuous vertical distribution of pH.

Experiment 3 would continue on Days 5 and 6 that would each include a 2-hour release at the 0.6 kg/s release rate. This would be monitored using the fixed instruments and instruments mounted on the ROV or manned submersible. A long-term (3 to 5 hours) survey would be conducted to examine the dispersion characteristics of the carbon-rich plume beyond the immediate vicinity of the discharge. At the conclusion of the last survey, the platform would be recovered from the bottom and hoisted onto the deck of its mother ship.

#### 4.2.5 NOZZLE EXCHANGE/CO<sub>2</sub> RESTOCKING

No experiments would be conducted on Day 7. The time would be spent changing the nozzle assembly, maintaining and repairing the equipment, conducting ROV or submersible dives and CTD casts and, if necessary restocking the CO<sub>2</sub>. If necessary, the mother ship might make port to pick up the additional CO<sub>2</sub> or parts. If this is not necessary, it would maintain position in the general area of the experimental site.

#### 4.2.6 DEPLOYMENT 2: SMALL NOZZLE (EXP 4)

The same activities would be conducted during the second deployment of the discharge platform as were conducted during the first. The only difference would be that this series of experiments would be conducted using a smaller nozzle assembly. This work would be conducted during Days 8 - 9. The last two days of the *Field Experiment* would be used to complete a post-release survey of the area with the submersible and to retrieve all the moored instrument packages.

### 4.3 CONTINGENCY PLANS

During conduct of experimental activities, a Chief Biologist shall be assigned as the final authority for decision-making regarding potential significance of observed effects on marine life and shall possess authority to modify (including the possibility of suspension or termination of a release of CO<sub>2</sub>) the experimental protocol after notification and discussion with the chief scientist. If a release is suspended or terminated, the chief biologist, after consultation with the chief scientist, the advisory group, and others, shall determine the schedule, conditions, and parameters for resumption of experimental activities. The experimental activities would be reviewed and, if necessary, modified under the following conditions:

The plans for the proposed experiment have been developed using the best available scientific information concerning the probable behavior of the cloud of CO<sub>2</sub> droplets and the plume of carbon-enriched water. The analysis that has been conducted to-date indicates that the release will have a very limited effect on water quality or biota. Real-time collection and display of pH data combined with visual monitoring of biota in the surrounding environment and the test organisms carried outside the ROV or submersible will provide researchers an immediate warning of unanticipated results. Spotters aboard ship will be dedicated to observation of the surface waters above the release site to provide early warning of any approaching threatened or endangered species as well as any unanticipated surfacing and flashing of CO<sub>2</sub>. The following criteria, among others, will be used by the Chief Biologist in his or her evaluation real-time evaluation of the *Field Experiment*.

- Scientists observe unusual mortality of the trapped organisms (e.g., amphipods, decapod shrimp and teleost fishes) carried on the outside of the ROV or manned submersible.<sup>4</sup>
- Biologists observe unusual mortality of fish, squid, or other free-swimming organisms in the water column. This decision will be based on the professional judgment of the scientist in charge of the biological component of the experiment.
- Biologists observe unusual mortality of benthic organisms.
- Scientists observe that a stream of CO<sub>2</sub> droplets is reaching the surface.
- pH levels below 6.0 are observed more than 100 meters from the point of release.
- Threatened or endangered species are observed by the submersible in the vicinity of the release point.
- Significant numbers of sensitive species are observed in the impacted area.
- Large aggregations of organisms are observed transiting the area in or near the CO<sub>2</sub> enriched plume.
- Noise levels measured by the hydrophones are substantially higher than expected and real-time visual observations by the project biologists indicate that these noise levels are affecting the behavior of macrofauna near the test platform.
- The spotters on the ship observe substantial aggregations of any threatened or endangered species.

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<sup>4</sup> Baited traps would be placed on the seafloor in the study area the day before the experiment. On the day of the experiment, one trap would be placed in the ROV or submersible's equipment rack where it can be observed in real-time using a video camera. A pH meter would be placed close to the trap.

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DESCRIPTION OF EXPERIMENTAL ACTIVITIES

The Chief Biologist will immediately suspend CO<sub>2</sub> release activities and communicate to the NMFS and the U.S. Fish & Wildlife Service if any substantial adverse impacts to threatened or endangered species are observed. The Chief Biologist will initiate consultation as appropriate.

**4.4 CLOSING NOTE**

The Environmental Assessment that was prepared for the proposed project conservatively assumed that as a worst-case, the platform could be deployed up to 10 times over the course of two weeks. As planning has progressed, it has been determined that the scientific objectives could be achieved with substantially fewer deployments of the platform.

The detailed scheduling described above assumes just two deployments. It is possible that equipment failure, the sudden arrival of adverse weather or sea conditions, or other factors could lead researchers to split the tests over as many as three additional deployments (for a total of 5). This would not substantially alter other aspects of the project.

## **APPENDIX D: CONCEPTS AND MODELS RELEVANT TO THE FIELD EXPERIMENT**

An understanding of the potential utility and environmental effects of ocean sequestration of CO<sub>2</sub> requires knowledge of natural processes that take place within widely different scales of time and space. One of the ways that scientists investigate such processes and their implications for ocean sequestration is through development of computer models. The models are developed using known physical principles to predict measurable consequences. Such models are supported, modified, and validated by oceanographic investigations that measure the actual causes and results in the real world.

The proposed *Field Experiment* is one example of this kind of investigation, and it is focused on the small scale. The following passages consider three different scales, global, mesoscale, and the small scale proposed for the experiment, and describe the relevance of the proposed *Field Experiment* to each. This is followed by a short description of the specific models that the *Field Experiment* is designed to support.

### **Global Scale**

A basic understanding of the relationship between CO<sub>2</sub> in the ocean and CO<sub>2</sub> in the atmosphere is necessary for appreciating the rationale for ocean sequestration of CO<sub>2</sub>. In general, regions of upwelling correspond to a transfer of CO<sub>2</sub> from the ocean into the atmosphere, while the highly alkaline waters of subtropical gyres, cold waters in high latitudes and biologically productive surface waters all absorb CO<sub>2</sub> from the atmosphere (Wong and Hirai 1997, p. 23-24).

The difficulties associated with the measurement of seasonally and locally varying carbon fluxes on the vast expanses of the entire oceanic surface are substantial. At a given time and location, these fluxes are proportional to the difference between  $p_a$ , the partial pressure of CO<sub>2</sub> in the atmosphere, and  $p_m$ , the partial pressure of free CO<sub>2</sub> in the mixed layer of the ocean. The coefficient of proportionality itself depends on various factors such as wind speed, local CO<sub>2</sub> solubility, etc. The net sink associated with the North Pacific Subtropical Gyre (NPSG), for example, was recently estimated to be 0.2 GtC/yr, over an area of  $26.3 \times 10^6$  km<sup>2</sup> (Winn *et al.* 1994). This value corresponds to a small partial pressure imbalance  $p_a - p_m$  of the order of 10  $\mu$ atm (or ppmv).

While our improved ability to measure detailed carbon fluxes is very important, especially for three-dimensional predictive tools such as Ocean General Circulation Models (OGCMs), some global knowledge already is available (Siegenthaler and Sarmiento 1993). On one hand, it is acknowledged that prior to the middle of the 19<sup>th</sup> Century, the pre-industrial atmosphere and ocean had been in global equilibrium for many centuries, with large fluxes across the ocean surface (of the order of 74 GtC/yr) balancing each other out. Today, not only have global carbon fluxes across the ocean surface increased (to about 90 GtC/yr), but more importantly, the mixed layer has become a net global carbon sink, of about 2 GtC/yr across an oceanic surface of about  $3.7 \times 10^8$  km<sup>2</sup>. The NPSG appears to be an average region, with local values aligned with global estimates.

Notwithstanding uncertainties that remain to be clarified, the net global carbon sink across the ocean surface can be attributed to current anthropogenic CO<sub>2</sub> emissions in the atmosphere (about 6 GtC/yr). In other words, the mixed layer of the ocean already has been absorbing the equivalent of one third of all atmospheric emissions from the burning of fossil fuels.

As CO<sub>2</sub> atmospheric emissions have been projected to rise sharply on a worldwide basis through the 21<sup>st</sup> Century, certain physical and chemical phenomena that play a crucial role in the carbon budget of the oceanic mixed layer should be succinctly discussed. It will be seen that, as a result of these mechanisms, the oceanic mixed layer represents a veritable bottleneck to the eventual transfer of excess atmospheric carbon to the deep ocean.

The mixed layer of the ocean is typically 60 to 75 m thick and lies between the atmosphere and the deep ocean. The upper reaches of the deep ocean, down to approximate depths of 1,000 m, constitute

the main (or permanent) thermocline. Because of the density stratification of the upper deep ocean, transport phenomena such as turbulent eddy diffusion (dispersion) are greatly inhibited. Vertical stability through the thermocline can be ‘visualized’ by imagining a tiny water blob moving up (down) into less (more) dense ambient water; it would immediately tend to sink (rise) back into its original position because of an imbalance between its weight and buoyancy.

Thus, a first limiting transfer mechanism affecting the mixed layer is the slow downward vertical migration of any excess carbon through the thermocline. Recent estimates of the vertical eddy diffusivity are actually one order of magnitude lower than previously thought (Wong and Matear 1996). As a result, the influence of the deep ocean in limiting the rise of atmospheric and mixed-layer carbon concentrations might not be felt over time scales of decades, when it would be most critical. It is noteworthy to add that this limitation also applies to the downward dispersion of heat. In other words, slow vertical dispersion through the main thermocline might also prevent a timely reduction of any temperature buildup (Global Warming) in the upper layers.

Going back to the flux of CO<sub>2</sub> across the ocean surface, another fundamental mechanism must now be described that limits the transfer of excess atmospheric CO<sub>2</sub> into the mixed layer. It was mentioned in previous sections that in seawater, several carbon species exist and that their relative amounts are controlled by the requirements of chemical equilibrium. Thus, when CO<sub>2</sub> is added to seawater, the amount of dissolved inorganic carbon (DIC) increases accordingly. In spite of the buffering (neutralizing) effect of carbonate ions (CO<sub>3</sub><sup>2-</sup>) on CO<sub>2</sub>, [CO<sub>2</sub>] increases sharply with [DIC] and the pH is reduced.

A fundamental result from the chemistry of carbon species in seawater is that with the addition of carbon, the relative increase in [CO<sub>2</sub>] greatly exceeds the relative increase in [DIC]. Since [CO<sub>2</sub>] is proportional to the free CO<sub>2</sub> partial pressure  $p_m$ , one can define the Revelle factor as:

$$= \{(p_m - p_{m0})/p_{m0}\} / \{([DIC] - [DIC]_0)/[DIC]_0\},$$

where the subscript 0 indicates a state of reference.

Currently,  $\alpha$  is of the order of 10, and is an increasing function of [DIC]. High values of  $\alpha$  indicate that the transfer of excess atmospheric carbon into the ocean’s mixed layer is rather difficult. Increasing values of  $\alpha$  with [DIC] mean that this transfer will get even more difficult as more carbon is released into the system. An intuitive explanation of this point can be stated as follows. A small relative increase in [DIC], which measures the storage capacity of the mixed layer, corresponds to a  $\alpha$ -fold relative increase in  $p_m$ . In turn, high values of  $p_m$  choke the flux of carbon into the mixed layer, which is controlled by  $p_a - p_m$ . In general, most CO<sub>2</sub> emitted into the atmosphere stays in the atmosphere, with only a small fraction being transferred into the ocean mixed layer.

The above discussion provides the fundamental tenet underlying the general concept of CO<sub>2</sub> Ocean Sequestration. The ocean mixed layer is a very narrow bottleneck inhibiting the transfer of the excess CO<sub>2</sub> from the atmosphere into the deep ocean. This bottleneck has two components: the import of carbon from the atmosphere into the mixed layer (the Revelle factor effect) is difficult, and the export of carbon to the deep ocean from the mixed layer (from the stratification of the main thermocline) is difficult. CO<sub>2</sub> Ocean Sequestration essentially calls for bypassing the ocean mixed layer. Moreover, the stratification of the upper deep ocean – an impediment to vertical dispersion – would now help confining CO<sub>2</sub> disposed directly into the deep ocean.

If one considers the potential for future large-scale implementation of CO<sub>2</sub> ocean sequestration, the feasibility of the concept and its environmental effects should be evaluated by OGCMs, preferably coupled with a climate model including the atmosphere, biosphere, surface ice, etc.

A dozen or so of these models are being developed and tested by various groups throughout the World. Currently, the prediction time scale for these models is from years to decades and centuries. The space scale is of the order of 100 km at the very least (the smallest grid size ever run on very powerful supercomputers is one degree, or 60 nautical miles). In addition to computer run time limitations, a better understanding of many complex mechanisms needs to be developed, and what occurs at sub-grid scales needs to be integrated as ‘input’ (in a generalized sense).

For an OGCM evaluation of the CO<sub>2</sub> ocean sequestration concept, the marine macro-scale biogeochemical cycle would be considered. A more commonly used term is “the biological pump” (Wong and Hirai 1997, p. 24-26). The detritus flux of organic matter sinking below the pycnocline accelerates the transfer of carbon to the deep ocean. The primary components of this ‘pump’ include the silicate and calcium carbonate exoskeletons from phytoplankton as well as the fecal matter from zooplankton that graze upon them.

Nitrogen, phosphorus, oxygen, and other elements all have their own global cycles as well. In the ocean, a fundamental coupling between these elements and carbon occurs via biological activity. The photosynthesis reaction itself is a striking illustration of such coupling. Some very interesting one-dimensional models have been published that show the role of marine biota on the overall compositional structure of the world oceans (Kheshgi and Flannery 1991).

Currently, ongoing OGCM evaluations of the CO<sub>2</sub> ocean sequestration concept try to include the cycling of as many elements as possible. However, the interaction of carbon that would be disposed in the ocean, with elements such as nitrogen for example, would take place indirectly, inasmuch as changes in the concentrations of inorganic carbon species, pH and alkalinity (if the dissolution of calcareous sediments occurs) would affect biological processes. The small scale and short duration of the *Field Experiment* do not lend themselves to a critical evaluation of the interplay between carbon and nitrogen cycles under CO<sub>2</sub> disposal scenarios.

A primary goal of OGCMs is to describe accurately the large-scale ocean currents in all their complexity. In this sense, they should be able to simulate the thermohaline “conveyor,” whereby deep water is formed in polar latitudes, and resurfaces elsewhere. Our understanding of this circulation has greatly evolved over the past decade (Wong and Hirai 1997, p. 46; Wong and Matear 1996).

Results from the proposed *Field Experiment* would not contribute directly to the understanding of these processes or to the validation or modification of OGCMs.

### **Mesoscale**

Phenomena that are just too small or perhaps too short-term to be yet modeled by OGCMs, but that develop in a matter of weeks or months and span dimensions of orders 10 to 100 km, are also important for the understanding of ocean sequestration. The Kona coast of the Big Island is an interesting example where mesoscale eddies often develop in the lee of the island. These eddies can even be generated in pairs: along the North Kona coast a cyclonic (counterclockwise) eddy, and along the South Kona coast, an anticyclonic (or clockwise) eddy (Flament, *et al.* 1997). Ke\_hole Point lies at the boundary of the formation zones of these eddies, and therefore may be subjected to the action of a cyclonic eddy, or of an anticyclonic eddy. In the former case, coastal waters experience a North running (Kohala) current, with the core area of upwelled water well offshore (order of tens of kilometers).

Wyrski *et al.* (1967) identified and characterized a cold-core cyclonic eddy off the North Kona coast well before the advent of satellite imagery. They performed oceanographic measurements down to 300 m in the course of two successive research cruises, in May and July of 1965. The eddy seemed to have formed within two months before the first cruise, and intensified between the May and July observations (inasmuch as the same eddy did persist for two months!). Its size was about 100 km. Data on the deformation of isotherms showed that the eddy was concentrated in the upper 300 m in

the earlier, less intense stage (May observations), but affected deeper water in July. Observations were not available for water deeper than 300 m, however.

Current measurements collected at Ke\_hole Point in August 1999 showed the presence of shear (horizontal current reversal) about 500 m below the surface while satellite data showed a strong mesoscale cyclonic eddy offshore (Sundfjord and Golmen 2000). These results suggest that the dynamic effects of mesoscale eddies along the Kona coast are mostly confined in waters shallower than 300 to 500 m.

The proposed *Field Experiment* is not designed to evaluate such oceanographic processes or the behavior of CO<sub>2</sub> releases at these temporal and spatial scales. Though the currents to be expected on the seabed at the *Field Experiment* site may be influenced indirectly by such eddies and other mesoscale processes, the proposed releases of CO<sub>2</sub> will not be large or persistent enough to be tracked long enough or far enough away from the release point to permit a credible study of the interactions between the released CO<sub>2</sub> and these natural processes.

### **The Field Experiment**

The size and duration of the controlled CO<sub>2</sub> releases planned during the *Ocean Sequestration of CO<sub>2</sub> Field Experiment* place the project at the low end of small-scale (local) dynamics. Time scales of hours to days, and spatial scales of tens of meters to a few kilometers characterize the regime of interest for the *Field Experiment*. The scientists involved with the project hope to investigate the near-field behavior of a CO<sub>2</sub> release to get a better understanding of the complex interactions between dissolving liquid CO<sub>2</sub> droplets and deep seawater. The natural processes that would control the behavior of the released CO<sub>2</sub> include tides, internal waves, localized solid boundary effects, and other processes.

The models developed to study the small-scale evolution of CO<sub>2</sub> that would be released in deep waters (buoyant rise, dissolution, dispersion, etc.) use computers just as powerful as the OGCMs, but deal with small-scale physics and grid sizes of the order of meters. Incidentally, more powerful computers would only increase the simulation times that can be calculated, or permit smaller grid sizes – great benefits *per se*, but would offer no insight on basic input sub-models (hydrate effects, droplet dissolution rates, droplet terminal velocities, etc.). In turn, it is not possible to replicate the complex stratified seawater column in a laboratory at the necessary sizes, especially because of high-pressure requirements.

Several groups have been developing specific models of the behavior of CO<sub>2</sub> when it would be released into deep seawater. There currently are two methods of approach: one relies on laboratory experiments conducted on the basis of similarity laws and on integral plume models; another involves the numerical solution of complex equations with powerful computers. In all cases, the *Field Experiment* would provide valuable data that would help dispel modeling uncertainties.

A group led by Dr. Adams at the Massachusetts Institute of Technology has spearheaded plume studies based on similarity analysis and integral plume models. Laboratory experiments conducted on fluids other than CO<sub>2</sub> that do not necessitate very high pressures and unrealistic tank sizes have provided results on plume behavior that have been interpreted in terms of non-dimensional numbers (these numbers combine different physical properties of the fluids). This establishes a basis for extrapolation to the case of liquid CO<sub>2</sub>. Integral plume models solve basic physical equations (conservation of mass, momentum, energy etc.) assuming that some of the complexity of the existing fields (such as velocities, concentrations etc.) can be simplified using, for example, pre-determined profiles (Gaussian, top-hat, etc.) as long as overall results can be validated by existing data. Such models also rely on several entrainment coefficients that characterize exchanges between different zones (plume core, outside etc.). This type of analysis has the potential to identify very subtle qualitative phenomena, such as the existence of multiple intrusion layers resulting from the peeling of dense seawater out of the core of a rising plume, or the possible separation of the cloud of droplets from the dense carbon-rich seawater in a cross flow (current). It is not obvious whether existing



computer-based models have sufficiently high spatial resolutions yet to predict such qualitative features. The inherent weakness of laboratory experiments, however, is that CO<sub>2</sub> and high-pressure seawater cannot directly be used. Also, integral plume models are based on a number of implied assumptions and they are not time-dependent.

One computer-based model that has been available and developed for more than three years is the three-dimensional (3-D) code of Dr. Alendal's group, at the Nansen Environmental and Remote Sensing Center (NERSC) in Norway. Seawater and CO<sub>2</sub> droplets are treated as two separate phases in a two-phase Computational Fluid Dynamics (CFD) solver of the basic momentum and continuity equations. Transport equations allow the mapping of temperature, salinity, carbon, and droplet density. The fact that CO<sub>2</sub> exists in the form of droplets (dispersed phase) is accounted for by the introduction of the "droplet density" parameter. The CO<sub>2</sub> and seawater phases interact through drag (as the buoyant droplets rise through the water column) and mass transfer (as carbon dissolves into seawater). From the results calculated by the CFD model's transport equations, pH can be determined from another set of equations describing carbon chemistry in seawater. The CO<sub>2</sub> injection nozzle is modeled in one numerical cell as a source term.

Other computer-based models developed to describe the behavior of liquid CO<sub>2</sub> injected in deep seawater share the same basic approach. Two such 3-D models were conceived by Dr. Sato of the University of Tokyo, and Dr. Chen of Japan's Research Institute of Innovative Technology for the Earth (RITE), respectively. Typical reasons for differences between computer-based model results are the size and resolution of numerical grids (i.e., how closely spaced "calculation points" are) and the choice of the relationships describing the interaction between CO<sub>2</sub> and seawater (dissolution rates and droplet slip velocity), including hydrate formation and droplet shape. There are also some differences in representing oceanic turbulence and current fields.

Recent work by these scientists and others indicates that the input relationships describing CO<sub>2</sub> droplet dissolution and droplet slip velocity are mostly responsible for differences between different predictions.